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Coastal and Hydraulics Laboratory

US Army Corps of Engineers®
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New Lock for Soo Locks and Dam, Model Investigations during 2006 – 2010, Sault Ste. Marie, Michigan, St. Mary's River

Hydraulic Model Investigation

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Final report

Prepared for U.S. Army Engineer District, Detroit
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and U.S. Army Engineer District, Huntington
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Abstract: The U.S. Army Corps of Engineers, Detroit District, requested that the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL) evaluate the hydraulic performance of the new lock proposed for construction at the Soo Locks project in Sault Ste. Marie, Michigan. The lock will replace the existing Davis and Sabin locks in the North Canal. Currently, the Poe Lock is the only facility at Soo Locks capable of handling the Great Lakes system's largest vessels which account for more than half of the potential carrying capacity of the Great Lakes fleet. A laboratory model study was performed to evaluate the lock filling and emptying system and ice lockage procedures. Model investigations between 2003 and 2005 were reported in Hite and Tuthill 2005.

This report provides results of additional model experiments performed during the period 2005 – 2010 for the new lock. Modifications including new intake and filling and emptying system designs were evaluated. Additional intake experiments were performed as a result of changing the upper approach to include an emergency gate. Additional lock chamber experiments were conducted to determine the performance of a new port design suggested from a value engineering study of the Type 15 Design Filling and Emptying System for non standard lock valve operations. Non standard valve operations may be necessary for maintenance or a malfunctioning valve. All tests were performed with a 21.5-ft lift. The upper pool el was 601.6 and the lower pool el was 580.1.

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Preface

The model investigation reported herein was authorized by the Headquarters, U.S. Army Corps of Engineers and was performed during the period July 2005 to October 2010. The experiments were performed by personnel of the Coastal and Hydraulics Laboratory, CHL, of the U.S. Army Engineer Research and Development Center, ERDC, under the general supervision of Dr. William D. Martin, Director of the Coastal and Hydraulics Laboratory, CHL; Jose E. Sanchez, Deputy Director of the CHL; Dr. Rose M. Kress, Chief of the Navigation Division, CHL; Dr. Richard B. Styles, Chief of the Navigation Branch, CHL, and Jeff Lillycrop, Technical Director for Navigation, CHL.

The experimental program was led by Joe E. Myrick (retired), James P. Crutchfield (retired), Keith K. Green, Danny M. Marshall, and Carlos Bislip-Morales under the supervision of Dr. John E. Hite, Jr., Leader, Locks Group. Model construction was completed by Joe A. Lyons, Charles R. Burr, and O. J. of the Model Shop, Department of Public Works (DPW), ERDC, under the supervision of John E. Gullett of the Model Shop. Data acquisition and remote-control equipment were installed and maintained by Tim E. Nisley, Information Technology Laboratory (ITL), ERDC. Data acquisition software was developed by Dr. B. W. McCleave (deceased), ITL. The report was written by Dr. Hite and co-authored and peer reviewed by Carlos Bislip-Morales.

During the course of the study Thomas MacFarland, David Sullivan and Darin White of U.S. Army Engineer District Huntington (LRH), and John Niemiec and Kurt Bunker of U.S. Army Engineer District Detroit (LRE) visited ERDC to observe model operation, review experiment results, and discuss model results.

At the time of publication of this report Dr. Jeffery P. Holland was Technical Director of ERDC and COL Kevin J. Wilson, EN, was Commander.

Unit Conversion Factors

Multiply	By	To Obtain
Cubic feet	0.02831685	cubic meters
Feet	0.3048	Meters
gallons (U. S. liquid)	3.785412 E-03	cubic meter
Knots	0.5144444	meters per second
Miles (U.S. statute)	1,609.347	Meters
pounds (mass)	0.45359237	Kilograms
tons (force)	8,896.443	Newtons
tons (2,000 pounds, mass)	907.1847	Kilograms

1 Introduction

1.1 Background

This report provides results of the additional model experiments performed during the period 2005 – 2010 for the proposed New Lock at Soo Locks, Sault St. Marie, St. Mary's River. A previous report by Hite and Tuthill (2005) was published and provided the results from the original scope of work for the model study of the new lock.

After further evaluation of the Type 12 Chamber Design recommended from the original model investigation and changes to the proposed design, additional experiments were necessary to determine the hydraulic performance of these changes. The Type 12 Chamber Design used baffles placed on the lock floor to achieve the desired distribution of flow during filling and emptying. There were long term maintenance concerns as well as concerns that the baffles might puncture the hull of a ship under extraordinary conditions. Changes to the upper lock approach were also made to include an emergency gate. Additional intake and lock chamber experiments were conducted to determine the performance of these new designs.

1.2 The prototype

The existing Soo Locks project consists of four locks, MacArthur, Poe, Davis, and Sabin. The locks are located side by side near the eastern extremity of Lake Superior on the St. Mary's River, which is the only water connection between Lake Superior and the other Great lakes (Figure 1). The Soo Locks form a passage around the St. Mary's River rapids. The MacArthur Lock was constructed in 1943 and is 800 ft in length and 80 ft in width. The Poe Lock is 1200 ft in length, 110 ft in width and was completed in 1968. The Davis and Sabin (closed) Locks are both 1350 ft in length, 80 ft in width and were constructed in 1914 and 1919, respectively. A U.S. Hydroelectric Power Plant is also located north of the locks. The project layout is shown in Figure 2.

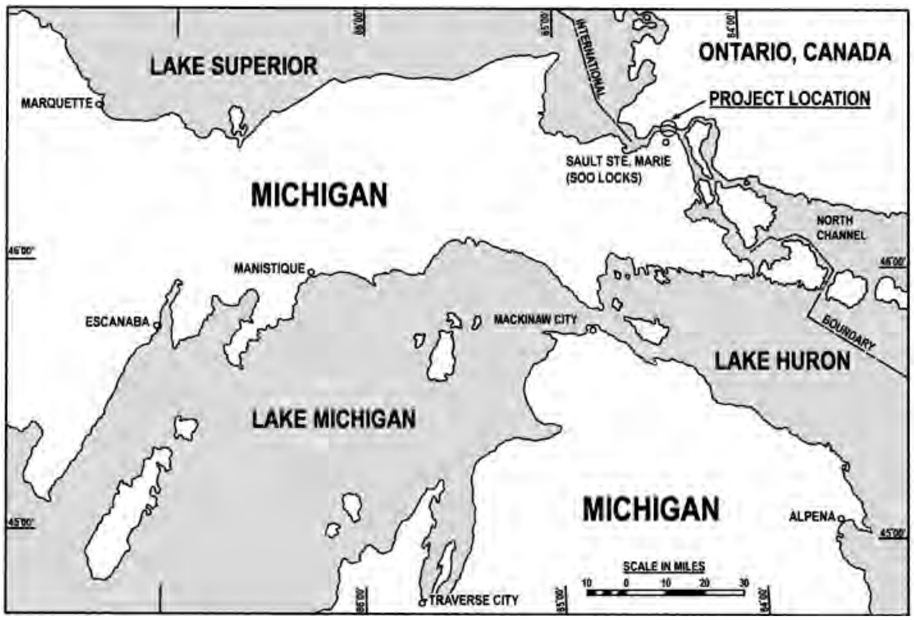

Figure 1. Vicinity map.

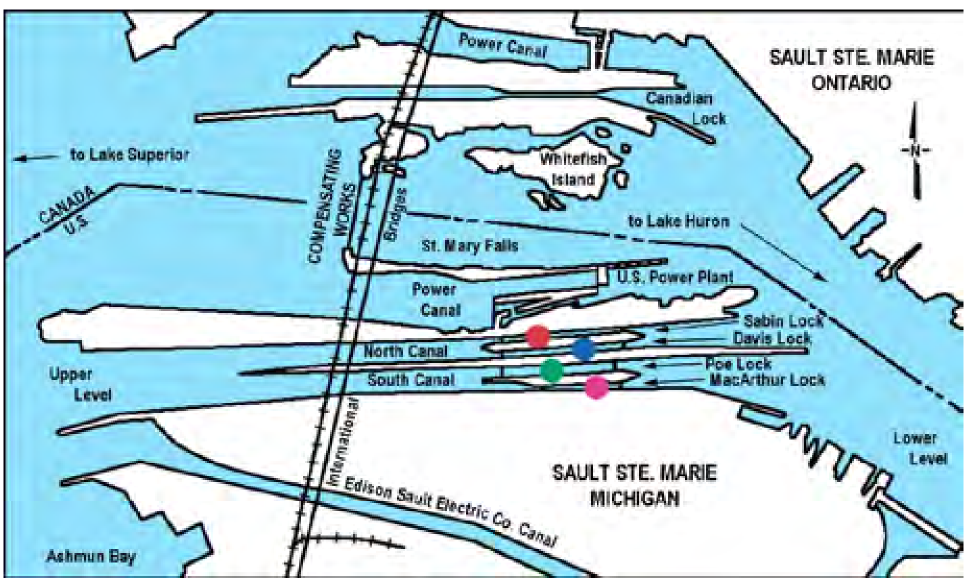

Figure 2. Layout of existing project.

1.3 Purpose and scope

The purpose of the physical model investigation was to evaluate the hydraulic performance of the lock filling and emptying system and make modifications to the design, if necessary, to achieve acceptable performance. Lock chamber performance was based on filling and emptying times, hawser forces, surface roughness and system energy losses. The intakes were evaluated based on vortex tendencies and the resulting flow patterns in the upper approach during lock filling.

2 Physical model

2.1 Description

The entire filling and emptying system was reproduced at a 1:25-scale along with approximately 500 ft lengths of the upper and lower approaches. Details of the original design model are provided in Hite and Tuthill (2005). Details of the subsequent modifications will be described in Chapter 3.

The filling and emptying system was fabricated from acrylic. The lock walls and floor and the upper and lower approaches were constructed from plastic coated plywood. The filling and emptying valves were made of brass.

2.2 Equipment and instrumentation

Water was supplied to the model through a circulating system. The upper and lower pools were maintained at near constant elevations during the filling and emptying operations using constant head skimming weirs in the model headbay and tailbay. During a typical filling operation, excess flow was allowed to drain over the weirs at the beginning of the fill operation and minimal flow over the weir was maintained at the peak discharge, thereby minimizing the drawdown in the upper reservoir. The opposite of this operation was performed during lock emptying. Upper and lower pool elevations were set to the desired level by adjusting the skimming weirs and reading piezometers placed in calm areas of the upper and lower pools. Water-surface elevations inside the chamber were determined from electronic pressure cells located in the middle and on each end of the lock chamber. Histories of the end-to-end water-surface differential were also recorded during filling and emptying operations. Dye and confetti were used to study subsurface and surface current directions. Pressures throughout the systems were measured with piezometers (open-air manometers). Pressures obtained in this manner are considered average pressures because of the reduction in frequency response resulting from the use of nylon tubing.

An automated data acquisition and control program, Lock Control[1] was used to control valve operations and collect pressure and strain gauge data. Fifteen data channels were used, eight for control of the filling and emptying valves, four for pressure data, and three for collecting strain gauge information. The data were collected usually at a sampling rate of 50 Hz. Some of the hawser force and lock filling and emptying data were collected at 10 Hz. These data were then processed using a computer program, LOCKDXF[2]. The processed data were used to determine lock filling and emptying times, longitudinal and transverse hawser forces, and differential pressures.

A hawser-pull (force links) device used for measuring the longitudinal and transverse forces acting on a tow in the lock chamber during filling and emptying operations is shown in Figure 3. Three such devices were used: one measured longitudinal forces and the other two measured transverse forces on the downstream and upstream ends of the tow, respectively. These links were machined from aluminum and had SR-4 strain gauges cemented to the inner and outer edges. When the device was mounted on the tow, one end of the link was pin-connected to the tow while the other end was engaged to a fixed vertical rod. While connected to the tow, the link was free to move up and down with changes in the water-surface in the lock. Any horizontal motion of the tow caused the links to deform and vary the signal, which was recorded with a personal computer using an analog-to-digital converter. The links were calibrated by inducing deflection with known weights. Instantaneous pressure and strain gauge data were recorded digitally with a personal computer.

2.3 Similitude considerations

2.3.1 Kinematic similitude

Kinematic similarity can be used for modeling of free-surface flows in which the viscous stresses are negligible. Kinematic similitude requires that the ratio of inertial forces ($pV^2\ L^2$) to gravitational forces (pgL^3) in the model are equal to those of the prototype. Here, p is the fluid density, V is the fluid velocity, L is a characteristic length, and g is the acceleration due to gravity. This ratio is generally expressed as the Froude number, $N_{F.}$

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[1] Written by Dr. Barry W. McCleave, Information Systems Development Division, Information Technology Laboratory, ERDC

[2] Written by Dr. Richard L. Stockstill, Navigation Branch, Coastal and Hydraulics Laboratory, ERDC

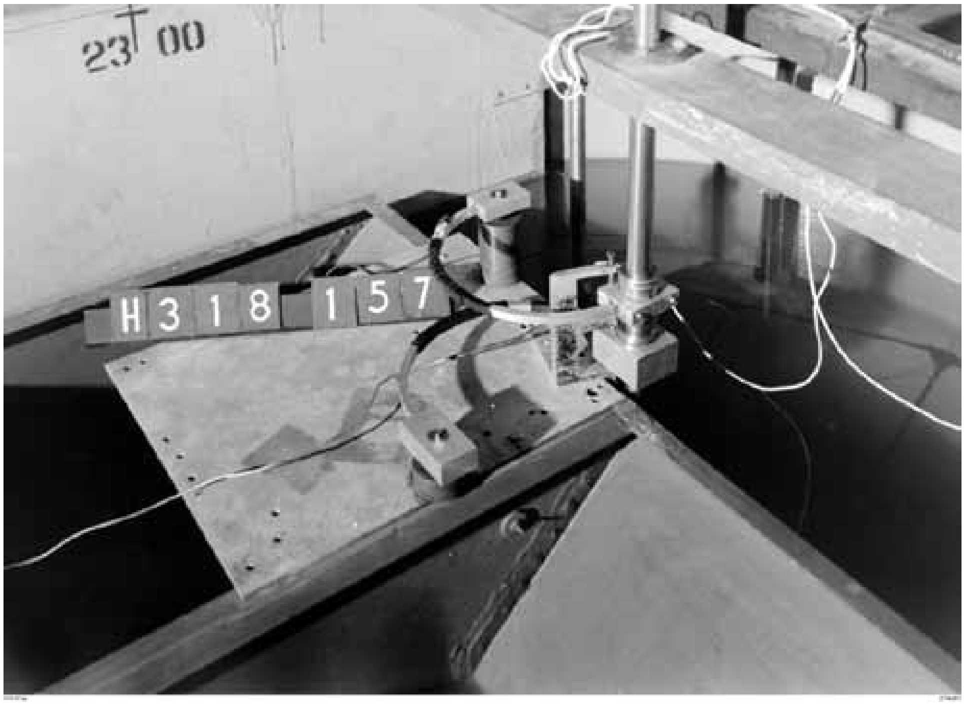


Figure 3. Hawser-pull (force links) measuring device.

$$N_F = \frac{V}{\sqrt{gL}} \tag{1}$$

where L, the characteristic length, is taken usually as the flow depth in open-channel flow.

The Froude number can be viewed in terms of the flow characteristics. Because a surface disturbance travels at celerity of a gravity wave, $(gh)^{1/2}$, where h is the flow depth, it is seen that the Froude number describes the ratio of advection speed to the gravity wave celerity. Evaluation of the lock chamber performance primarily concerns modeling of hawser forces on moored barges during filling and emptying operations. These hawser forces are generated primarily by slopes in the lock chamber water-surface. The tow's bow-to-stern water-surface differentials are the result of long period seiches or oscillations in the lock chamber. Seiching is gravity waves traveling in the longitudinal direction from the upper miter gates to the lower miter gates.

2.3.2 Dynamic similitude

Modeling of forces is a significant purpose of the laboratory investigation. Appropriate scaling of viscous forces requires the model be dynamically similar to the prototype. Dynamic similarity is accomplished when the ratios of the inertia forces to viscous forces (μ*VL*) of the model and prototype are equal. Here, μ is the fluid viscosity. This ratio of inertia to viscous forces is usually expressed as the Reynolds number

$$N_R = \frac{VL}{v} \tag{2}$$

Where v is the kinematic viscosity of the fluid (v = μ/ p) and the pipe diameter is usually chosen as the characteristics length, L, in pressure flow analysis.

2.3.3 Similitude for lock models

Complete similitude in a laboratory model is attained when geometric, kinematic, and dynamic similitudes are satisfied. Physical models of hydraulic structures with both internal flow (pressure flow) and external flow (free surface) typically are scaled using kinematic (Froudian) similitude at a large enough scale so that the viscous effects in the scaled model can be neglected. More than 50 model and 10 prototype studies of lock filling and emptying systems have been investigated (Pickett and Neilson 1988). The majority of these physical model studies used a scale of 1 to 25 (model to prototype). Lock model velocities scaled using kinematic similitude (model Froude number equal to prototype Froude number) in a 1: 25-scale model have maximum Reynolds numbers at peak discharges on the order of 10^5, yet the corresponding prototype values are on the order of 10^7.

Boundary friction losses in lock culverts are described empirically using the “smooth-pipe” curve of the Darcy-Weisbach friction factor where the headloss is expressed as

$$H_f = f\ \frac{L}{D}\ \frac{V^2}{2g} \tag{3}$$

where H_f is the headloss due to boundary friction, f is the Darcy-Weisbach friction factor, L is the culvert length, and D is the culvert diameter. The Darcy-Weisbach friction factor for turbulent flow in smooth pipes is given in an implicit form (Vennard and Street 1982)

$$\frac{1}{\sqrt{f}} = 2.0\log\left(NR\sqrt{f}\right) - 0.8 \tag{4}$$

Because *f* decreases with increasing N_R, the model is hydraulically "too rough". The scaled friction losses in the model will be larger than those experienced by the prototype structure. Consequently, the scaled velocities (and discharges) in the model will be less and the scaled pressures within the culverts will be higher than those of the prototype. Low pressures were not a major concern with the Soo Lock design; however, the lower discharges would in turn result in longer filling and emptying times in the model than the prototype will experience. Prototype filling and emptying times for similar designs will be less than those measured in a 1:25-scale lock model.

Modeling of lock filling and emptying systems is not entirely quantitative. The system is composed of pressure flow conduits and open-channel components. Further complicating matters, the flow is unsteady. Discharges (therefore N_F and N_R) vary from no flow at the beginning of an operation to peak flows within a few minutes and then return to no flow at the end of the cycle. Fortunately though, engineers now have about 50 years of experience in conducting large-scale models and subsequently studying the correspon-ding prototype performance. This study used a 1:25-scale Froudian model in which the viscous differences were small and could be estimated based on previous model-to-prototype comparisons. Setting the model and prototype Froude numbers equal results in the following relations between the dimensions and hydraulic quantities. These relations were used to transfer model data to prototype equivalents and vice versa.

Characteristic	Dimension[1]	Scale Relation Model :Prototype
Length	$L_r = L$	1:25
Pressure	$P_r = L_r$	1:25
Area	$A_r = L_r^{2}$	1:625
Velocity	$V_r = L_r^{1/2}$	1:5
Discharge	$Q_r = L_r^{5/2}$	1:3,125
Time	$T_r = L_r^{1/2}$	1:5
Force	$F_r = L_r^{3}$	1:15,625

[1]Dimensions are in terms of length.

3 Model experiments and results

The following paragraphs describe modifications that were made after the results from original scope of work were completed and published. For additional information on the previous designs evaluated, refer to Hite and Tuthill (2005).

3.1 Type 8 Intake Design

A design change proposed for the upper lock approach was the installation of an emergency gate with the sill for the gate located 125 ft upstream from the face of the intake, as shown in Figures 4 and 5. The emergency gate would be in the submerged position if not in use and when raised, the bottom of the gate would rest on the emergency gate sill at el 568.4. The emergency gate was not modeled for these experiments since it would normally be submerged and would not significantly affect flow over the emergency gate sill. Experiments were performed to document vortex activity in the upper approach during filling with different valve speeds. The upper pool el was 601.6 and the lower pool was 580.1 during these tests. The intake ports were flush with the intake face for these experiments. Vortex activity was documented on the left and right sides of the upper approach with valve operations of 3, 5, and 8 min. The Alden Research Lab vortex strength classification scale, Figure 6, was used to determine the strength of the vortex based on visual observations. The scale classifies a coherent surface swirl as a Type 1 vortex (weak) and a vortex with a full air core that enters the intake as a Type 6 vortex (very strong). Vortices stronger than Type 3 that form in a 1:25-scale model indicate a potential for strong vortex formation in the prototype. Time histories of vortex strength documented during the experiments are shown in Figure 7. Vortex formation on the right side was more prevalent than the left side. The strongest vortex observed was a Type 3 and occurred with the 5- and 8-min filling valve operations.

3.2 Type 9 Intake Design

The outer face surrounding the intakes was removed to form the Type 9 Intake Design shown in Figure 8. Experiments were repeated with the 3-, 5-, and 8-min valve operations. The time histories of vortex strength from these experiments are shown in Figure 9. Type 5 vortices were observed on

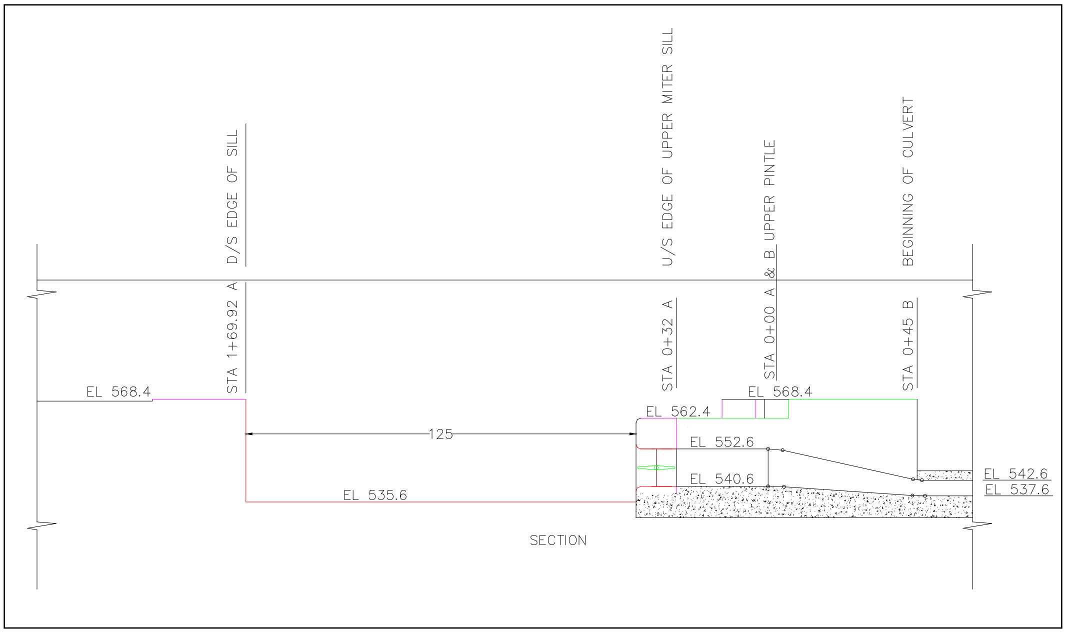


Figure 4. Section view of Type 8 Intake Design (Dimensions are in ft).

Figure 5. View looking upstream of location for emergency gate in upper approach.

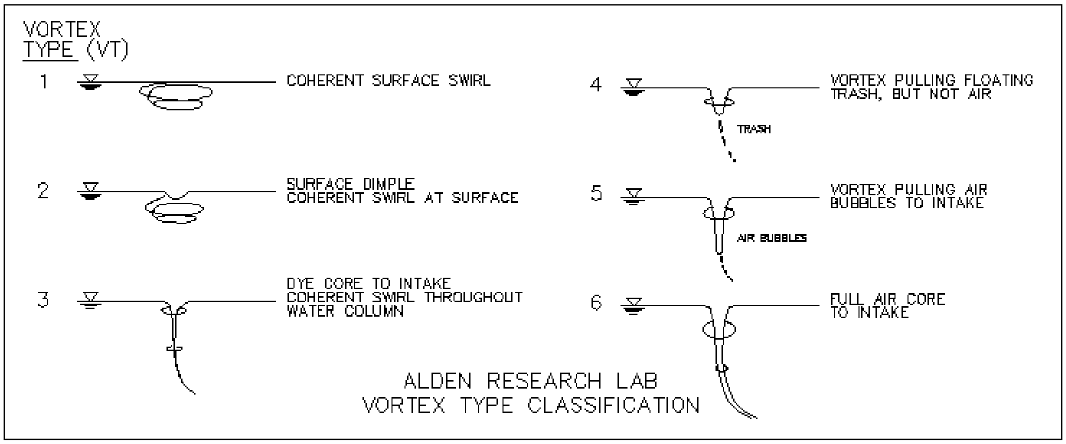


Figure 6. Vortex strength classification.

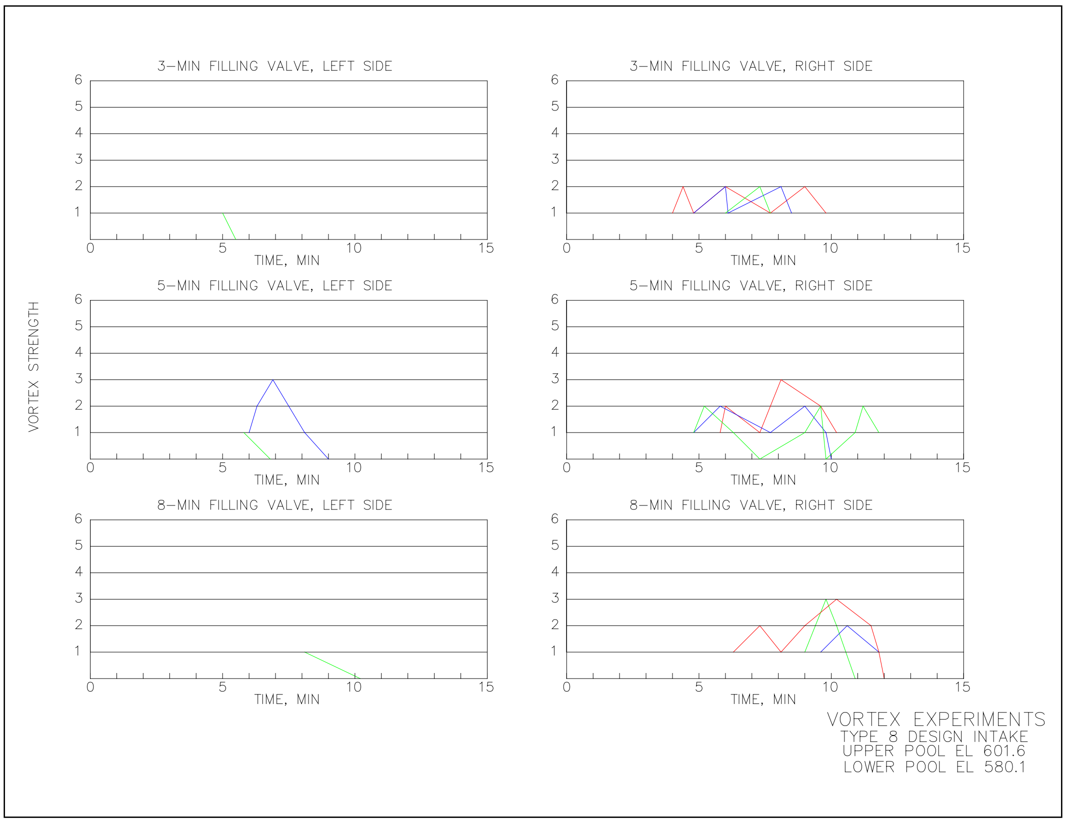


Figure 7. Time histories of vortex formation with Type 8 Intake Design (Colors represent different tests).

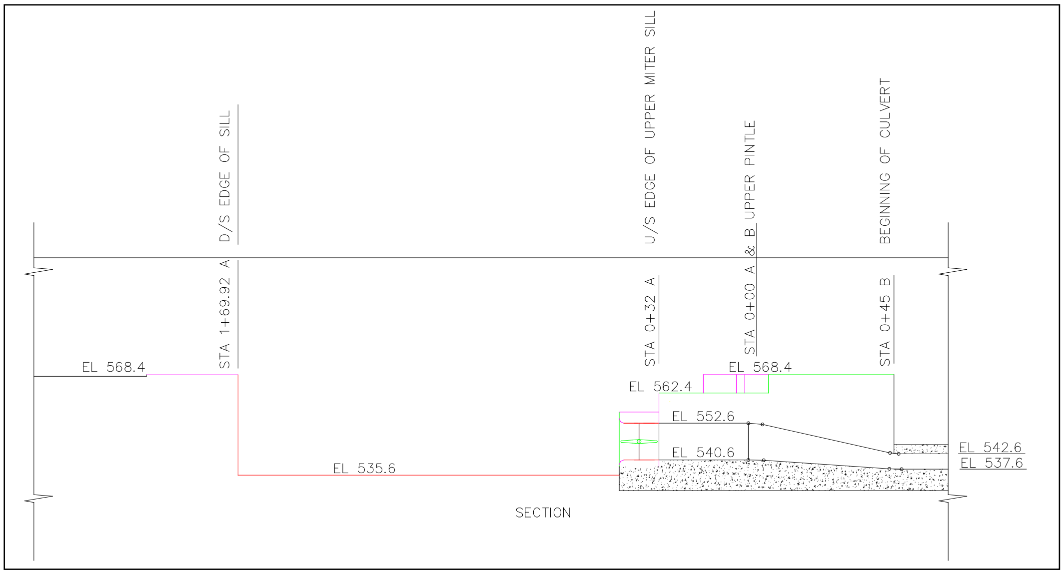


Figure 8. Section view of Type 9 Intake Design.

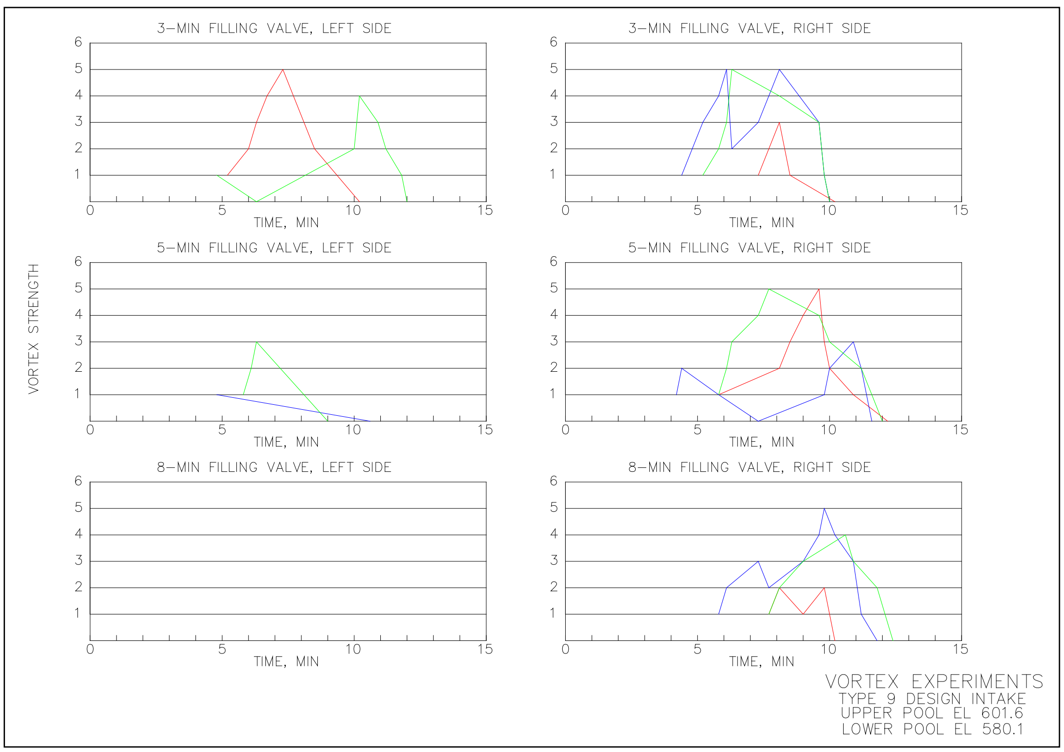


Figure 9. Time histories of vortex formation with Type 9 Intake Design (colors represent different tests).

the right side of the intake for all three valve operations and a Type 5 vortex was also observed in one experiment on the left side with the 3-min valve operation. Removing the intake face caused a significant increase in vortex strength in the upper approach. The intakes acted similarly to a reentrant entry increasing the headlosses and circulation. The Type 9 Intake Design has the potential for strong vortex formation.

3.3 Type 13 Chamber Design

As a result of a value engineering study, performed for the New Soo Lock the port design evaluated in Hite and Tuthill (2005) was changed. For reference, Figure 10 shows plan, section, and elevation views of the Type 12 Chamber Design. The intent of the new design was to achieve the redirection of flow from the upper ports and baffling effects of the lower ports obtained with the Type 12 Chamber Design without having baffles placed on top of the lock floor. The Type 13 Chamber Design attempted to include these features within the 3 ft thickness of the culvert roof. The center of each port in plan view remained in the same location as those with the Type 12 Chamber Design. Figure 11 shows an enlarged view of the upper and lower ports for the Type 13 Chamber Design. The upper port is angled upstream and the horizontal baffle in the lower port, that was located 3 ft above the floor with the Type 12 Chamber Design, was within the 3ft-thick culvert roof.

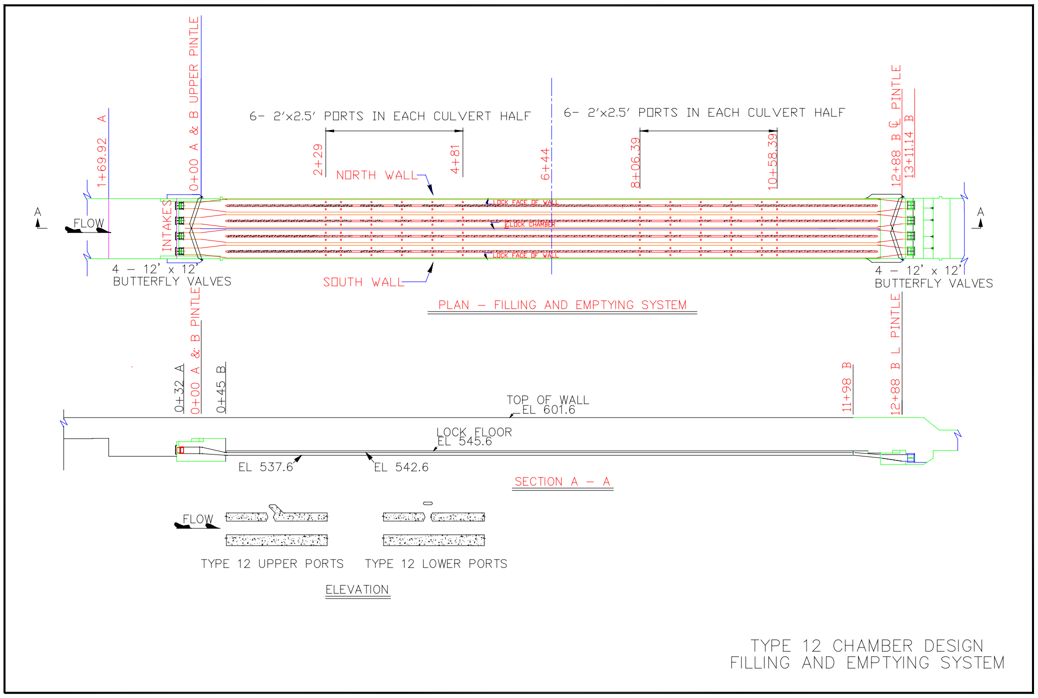


Figure 10. Type 12 Chamber Design.

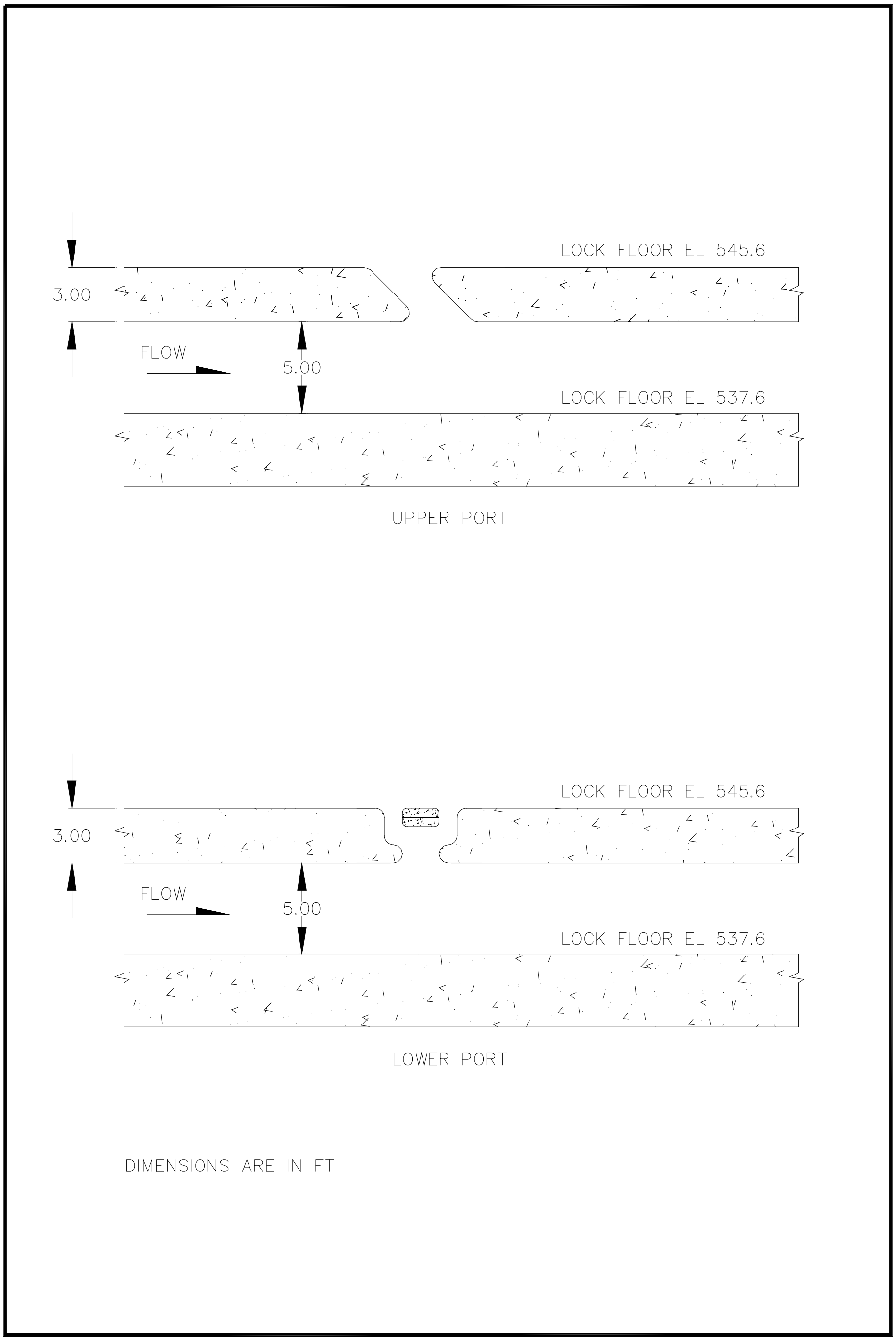


Figure 11. Side view of Type 13 Chamber Ports, ports are 3 ft in height.

3.3.1 Hawser force measurements with Type 13 Chamber Design

Hawser forces were measured with an upper pool el of 601.6 and a lower pool el of 580.1 for varying valve operations during filling and emptying to determine the permissible lock operation times. The recommended valve operation during filling determined from previous experiments with the Type 12 Chamber Design was 7 min and the permissible filling time was

13 min. The permissible filling time was determined by measuring hawser forces for multiple filling experiments with varying valve opening operations (time). The Corps guidance for maximum allowable hawser forces for a ship of this size and draft is 15 tons. The filling time associated with the valve opening operation that results in hawser forces of 15 tons is considered the permissible filling time.

Since the performance of the Type 13 Chamber Design was uncertain, a slow initial valve opening operation time of 14 min was used. Typical time histories obtained with the Type 13 Chamber Design and a 14-min valve operation are shown in Figure 12. The maximum longitudinal hawser force measured during the experiment was 27.7 tons in the downstream direction and occurred around 9 min into the filling operation. The transverse hawser forces were much less with a maximum of 3.5 measured on the right (looking downstream) side on the downstream transverse hawser ring. The filling time determined with the Type 13 Chamber Design and a 14-min valve operation was 18.5 min. The results from this experiment showed that a slower valve was needed to reduce the longitudinal hawser forces. The longitudinal hawser force measurements showed that after about 2 min into the filling operation, the hawser forces remained in a downstream direction. This is an indication that more flow enters the chamber from the upper ports. There was considerably more headloss in the lower port design with the Type 13 Chamber Design than with the Type 12 Chamber Design.

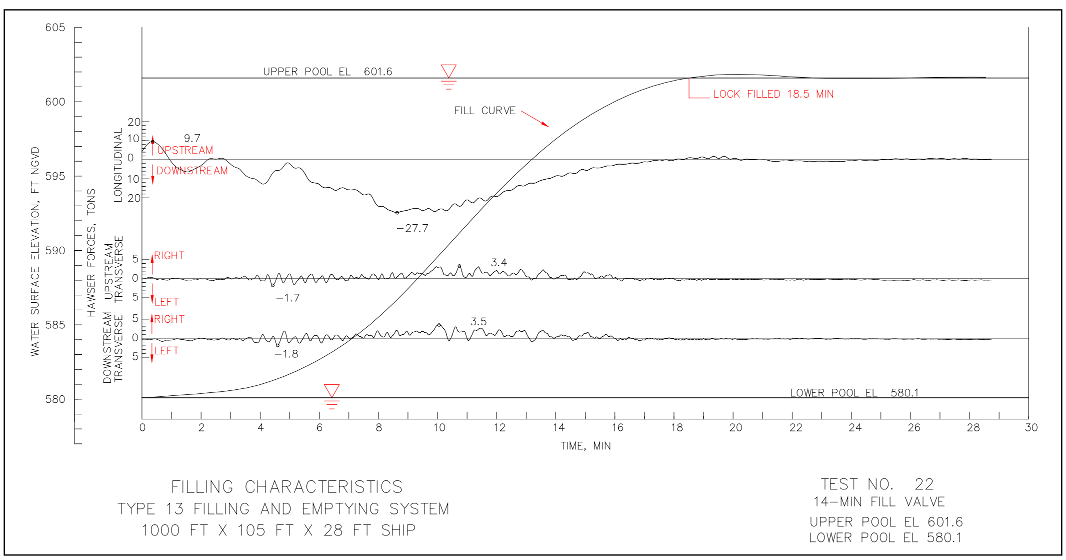


Figure 12. Time histories of water-surface and hawser forces during lock filling with Type 13 Chamber Design and a 14-min valve operation.

Figure 13 shows the average maximum hawser forces measured with the Type 13 Chamber Design during lock filling. The longitudinal hawser forces are much higher than the transverse hawser forces. The filling time to maintain hawser forces of 15 tons or less, interpolated from the plot of downstream longitudinal hawser forces, is 24.6 min. This is 11.6 min slower than the Type 12 Chamber Design. Table 1 shows the values used to produce the plots in Figure 13.

Hawser forces were measured during emptying for a 6-min valve opening. Typical time histories with the 6-min valve operation are shown in Figure 14. The maximum hawser force that occurred was 10 tons in the downstream direction just after 3 min into the emptying operation. The lock emptied in 14.2 min. The average maximum downstream hawser force determined for the 6-min valve with the Type 13 Chamber Design was 9.6 tons. This compares to 7.6 tons and 14.5 min determined with the Type 12 Chamber Design. The chamber performance during emptying was similar to that observed with the Type 12 Chamber Design. The permissible emptying time was 12.4 min.

3.4 Summary of Types 8 and 9 Intake Designs and Type 13 Chamber Design

Results from the intake vortex experiments with the Types 8 and 9 Intake Designs showed that vortex activity increased significantly without the intakes mounted flush with a face wall. Moving the sill for the emergency gate 125 ft upstream from the intake face did not cause increased vortex activity from that observed with the Type 6 Intake Design from the previous study, as long as the intakes were mounted flush with a face wall. The results from the hawser forces experiments showed that the Type 13 Chamber Design was considerably slower than the Type 12 Chamber Design during filling. During emptying, the chamber performance observed with the Type 13 Chamber Design was similar to that observed with the Type 12 Chamber Design. To improve the filling operation, the lower port design would need to be changed to reduce the headlosses and this would likely result in an unbalanced condition during lock emptying. The Type 13 Chamber Design did not improve the lock performance and additional modifications were necessary.

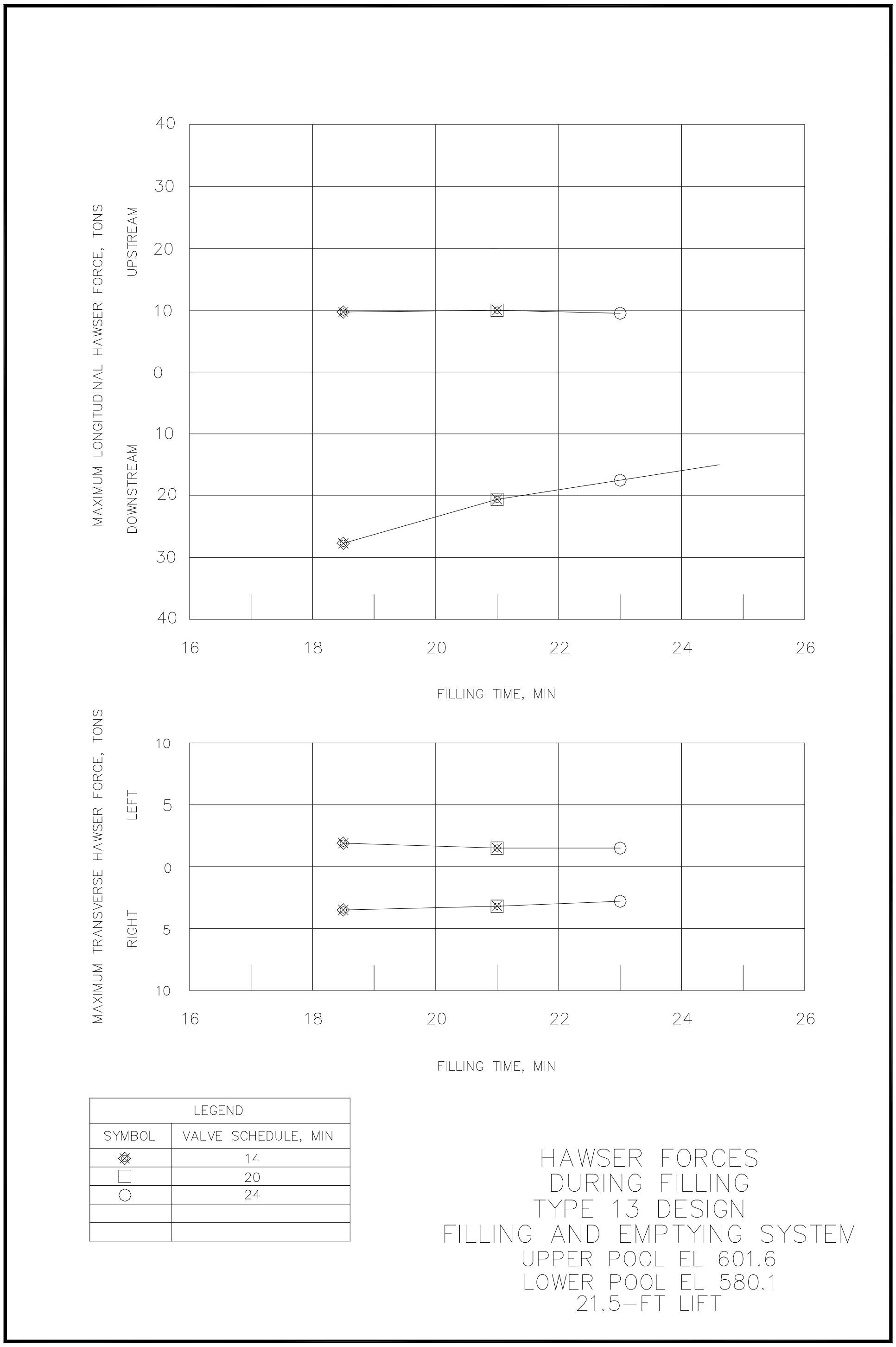


Figure 13. Average maximum hawser forces during filling with the Type 13 Chamber Design.

Table 1. Filling characteristics, Type 13 Chamber Design, 21.5-FT lift, upper pool el 601.6, lower pool el 580.1.

	Hawser Forces (Tons)						
	Longitudinal		U/S Transverse		D/S Transverse		
Valve Time (min)	U/S	D/S	Right	Left	Right	Left	Fill Time (min)
14.0	10.3	-28.1	3.8	-1.9	3.5	-1.7	18.5
	9.7	-27.2	3.1	-2.0	3.5	-1.8	18.7
	9.7	-27.7	3.4	-1.7	3.5	-1.8	18.5
Average	9.9	-27.7	3.4	-1.9	3.5	-1.8	18.6
20.0							
	10.4	-20.6	3.2	-1.6	2.6	-1.6	21.0
	9.7	-21.5	3.1	-1.4	3.5	-1.1	21.0
Average	10.0	-20.6	3.2	-1.5	3.0	-1.4	21.0
24.0							
	9.3	-17.5	2.9	-1.5	3.0	-1.4	23.0
	9.2	-17.6	2.5	-0.8	2.7	-0.8	23.0
	10.0	-17.3	2.7	-1.5	2.7	-1.3	23.1
Average	9.5	-17.5	2.7	-1.5	2.8	-1.4	23.0

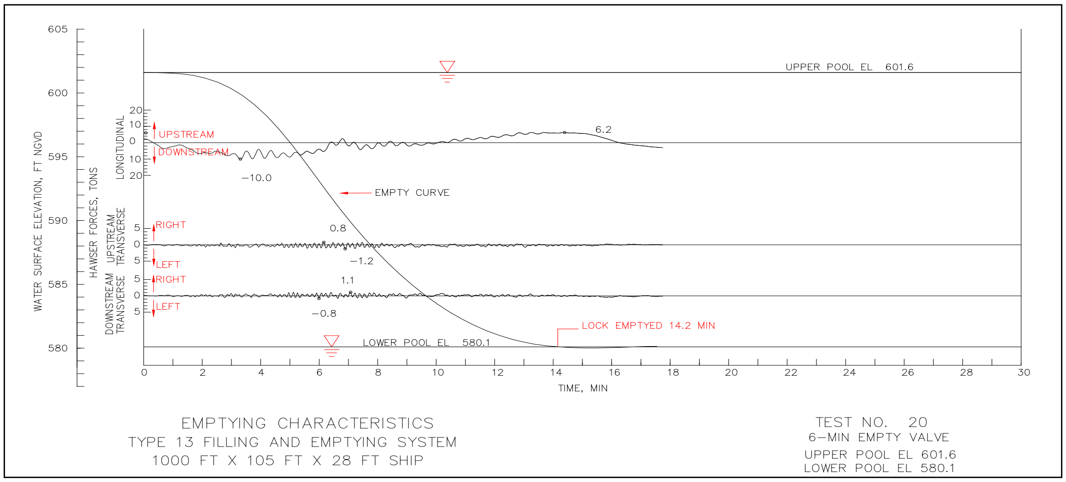


Figure 14. Typical time histories of water-surface and hawser forces during lock emptying with Type 13 Chamber Design and a 6-min valve operation.

3.5 Type 14 Chamber Design

The Type 14 Chamber Design was developed to try and improve the lock chamber performance and reduce the filling and emptying times determined with the Type 13 Chamber Design. The lock floor was raised from el 545.6 to el 546.7. The culvert invert transitioned from el 538.7 to el 535.7 upstream from the upper filling ports, which allowed the floor thickness to increase from 3 ft to 6 ft. The invert remained at this elevation through the upper ports and then the culvert invert transitioned back to 538.7 before reaching the lower ports. The lower ports were similar in design to the original design ports (no horizontal baffles were used for the lower ports in the Type 14 Chamber Design). Figure 15 shows a profile view of the Type 14 Chamber Design upper ports and Figure 16 shows a close-up of the upper and lower ports. This design provided a vertical port thickness of 6 ft and actual port length of 8.5 ft (length along 45 degree angle). This port length was greater than the Type 13 Chamber Design port.

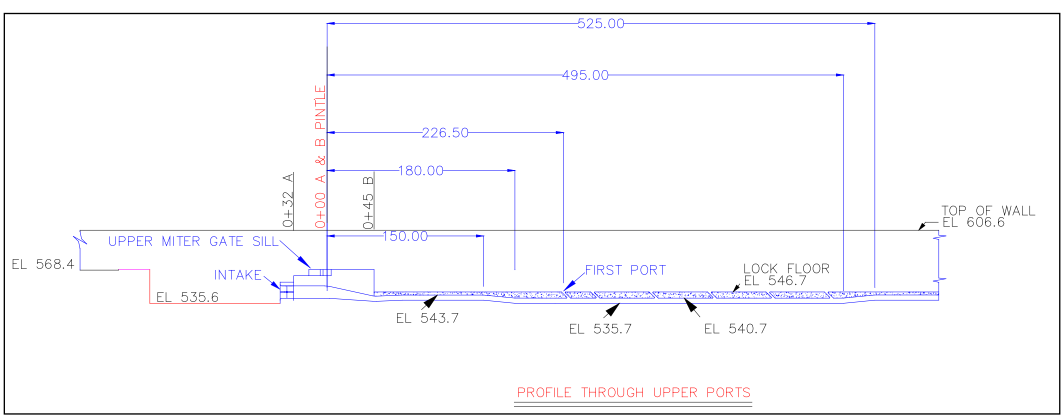


Figure 15. Profile view for upper ports in Type 14 Chamber Design, dimensions are in ft.

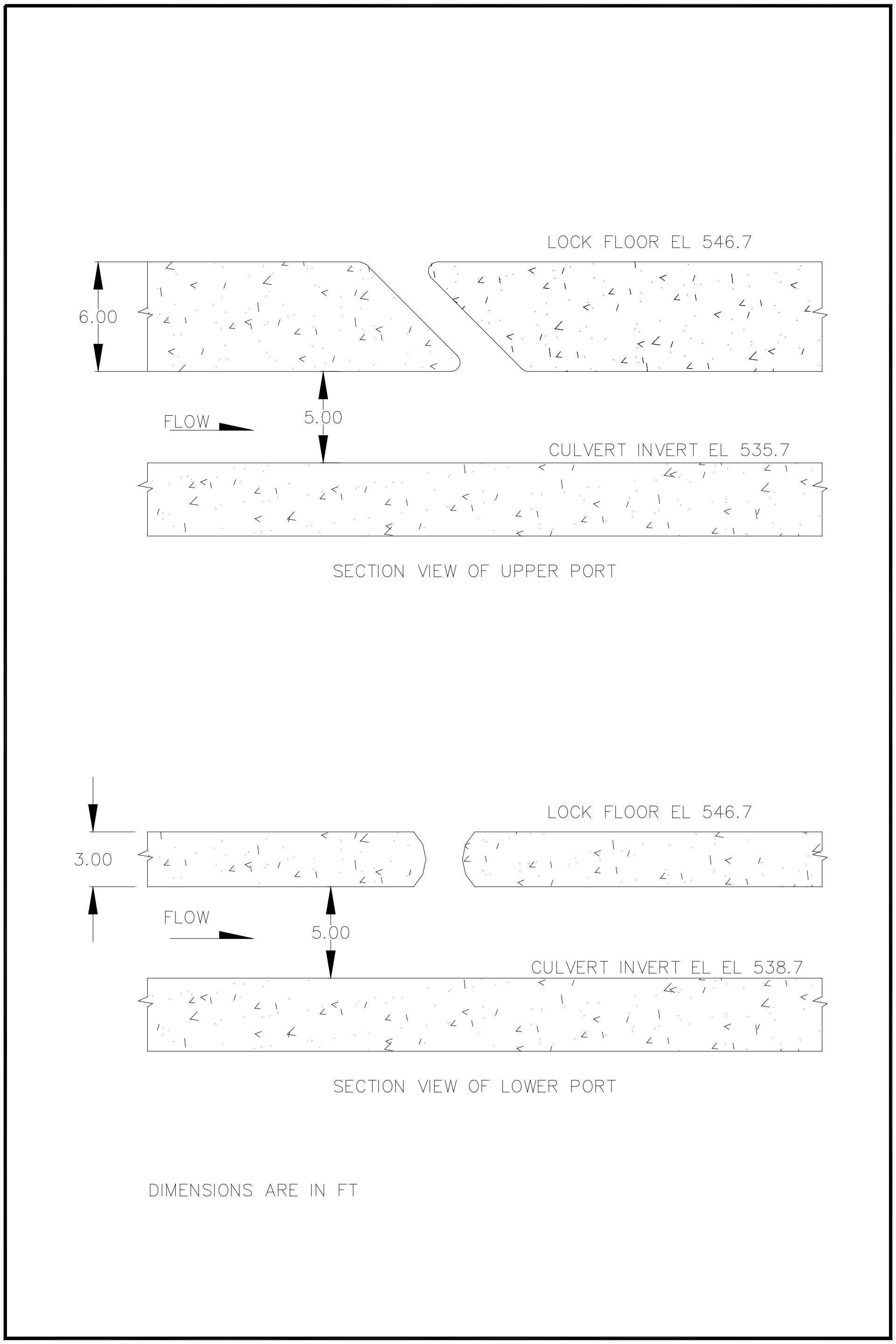


Figure 16. Section view of Type 14 Chamber Design ports.

3.5.1 Hawser force measurements with Type 14 Chamber Design

Hawser forces were measured with an upper pool el of 601.6 and a lower pool el of 580.1 for varying valve operations during filling and emptying to determine the permissible lock operation times. The initial valve opening time evaluated for the Type 14 Chamber Design was 10 min. Experiments with valve opening times of 20 and 26 min were also conducted. Typical time histories obtained with the Type 14 Chamber Design and a 10-min valve operation are shown in Figure 17. The maximum longitudinal hawser force measured during the experiment was 34.4 tons in the downstream direction and occurred around 6.5 min into the filling operation. The transverse hawser forces were much less with a maximum of 4.8 tons measured on the left (looking downstream) side at the downstream end of the chamber. The filling time determined with the Type 14 Chamber Design and a 10-min valve operation was 16.1 min. The results from these experiments showed that slow valve operations were needed to keep the longitudinal hawser forces from becoming excessive. The goal for a filling and emptying system for a ship with this weight is to keep hawser forces under 15 tons and still have acceptable filling and emptying times. The longitudinal hawser force measurements with the 10-min valve operation showed that between 1 and 14 min into the filling operation, the hawser forces remained in a downstream direction. This is an indication that the water-surface in the upper end of the chamber remains higher than the lower end during this period. The maximum upstream longitudinal hawser forces generally occurred right after the valve operation began.

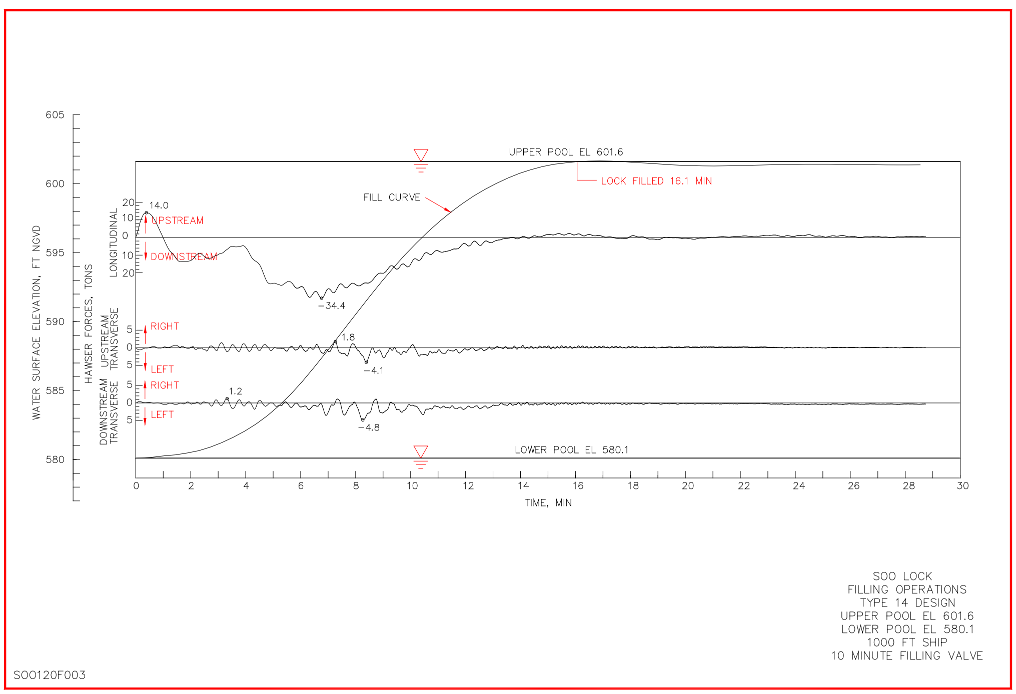


Figure 17. Typical time histories with Type 14 Chamber Design and 10-min filling valve.

Figure 18 shows the average maximum hawser forces measured with the Type 14 Chamber Design during lock filling with 10-, 20- and 26-min valve operations. Table 2 shows the values used to produce the plots in Figure 18. The longitudinal hawser forces are much higher than the transverse hawser forces. The filling time to maintain hawser forces of 15 tons or less, interpolated from the plot of downstream longitudinal hawser forces, is 23.0 min. This is 10 min slower than the Type 12 Chamber Design and only 1.6 min faster than the Type 13 Chamber Design.

An emptying experiment was performed with an 8-min valve operation to observe chamber performance during emptying. Times histories of the water-surface and hawser forces measured with the 8-min valve operation are shown in Figure 19. The maximum downstream longitudinal force was 6.4 tons and occurred around 5 min into the emptying operation. The hawser forces remained in the downstream direction during most of the empting operation indicating the downstream ports were slightly more efficient than the upstream ports. This experiment indicated that emptying operations would not be a factor for the performance of the Type 14 Chamber Design so permissible emptying times were not determined.

3.5.2 Summary with Type 14 Chamber Design

Results from the lock chamber experiments showed that the Type 14 Chamber Design was considerably slower than the Type 12 Chamber Design during filling and only slightly faster than the Type 13 Chamber Design. More flow discharged through the upper ports and less flow through the lower ports due to the headlosses in the culvert. During emptying, the chamber performance observed with the Type 14 Chamber Design was slower than that observed with the Type 12 Chamber Design. This is also an indication that this design has more headlosses than the previous designs evaluated. The Type 14 Chamber Design did not improve the lock performance. Additional experiments were necessary to develop a satisfactory filling and emptying system.

3.6 Type 15 Chamber Design

Personnel from Detroit District, Huntington District, and ERDC met to discuss the results from previous experiments and develop a new filling and emptying design. This design was designated the Type 15 Chamber Design and consisted of four 14-ft wide by 7-ft high culverts that convey flow to eight 7-ft wide by 7-ft high ported culverts. The water was supplied to these

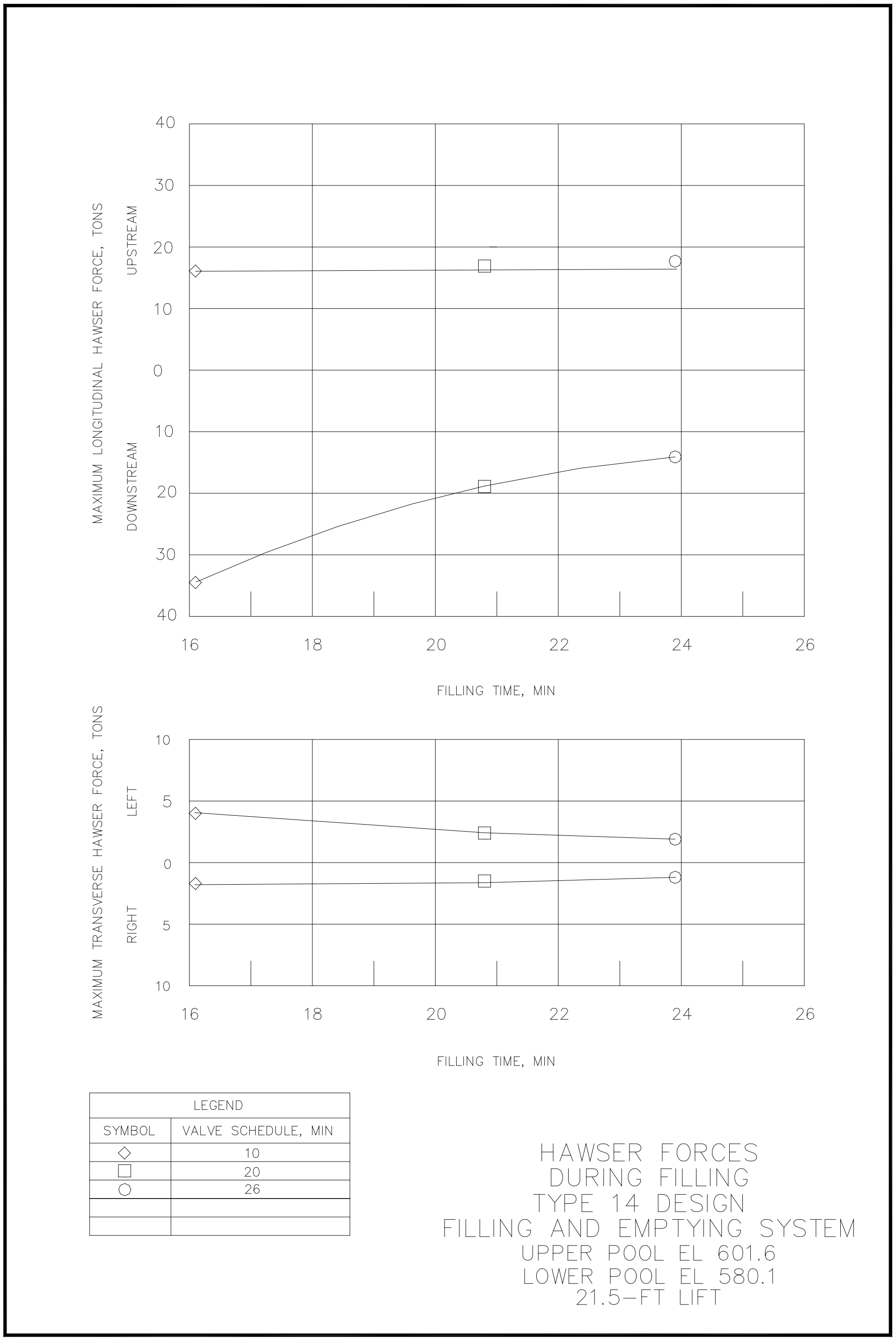


Figure 18. Average maximum hawser forces during filling with Type 14 Chamber Design.

Table 2. Filling Characteristics, Type 14 Chamber Design, 21.5-Ft lift, upper pool el 601.6, lower pool el 580.1.

Valve Time (min)	Hawser Forces (Tons)						Fill Time (min)
	Longitudinal		U/S Transverse		D/S Transverse		
	U/S	D/S	Right	Left	Right	Left	
10.0	14.0	-34.4	1.8	-4.1	1.2	-4.8	16.1
	18.2	-34.6	1.6	-3.3	1.8	-3.2	16.0
Average	16.1	-34.5	1.7	-3.7	1.5	-4.0	16.1
20.0							
	16.7	-18.9	1.6	-2.6	1.8	-2.6	20.9
	17.0	-18.9	1.4	-2.4	1.2	-2.2	20.8
Average	16.9	-18.9	1.5	-2.5	1.5	-2.4	20.9
26.0							
	17.6	-14.1	1.1	-1.8	1.3	-1.5	23.7
	17.8	-14.0	0.9	-1.9	1.0	-1.6	24.0
Average	17.7	-14.1	1.0	-1.9	1.2	-1.6	23.9

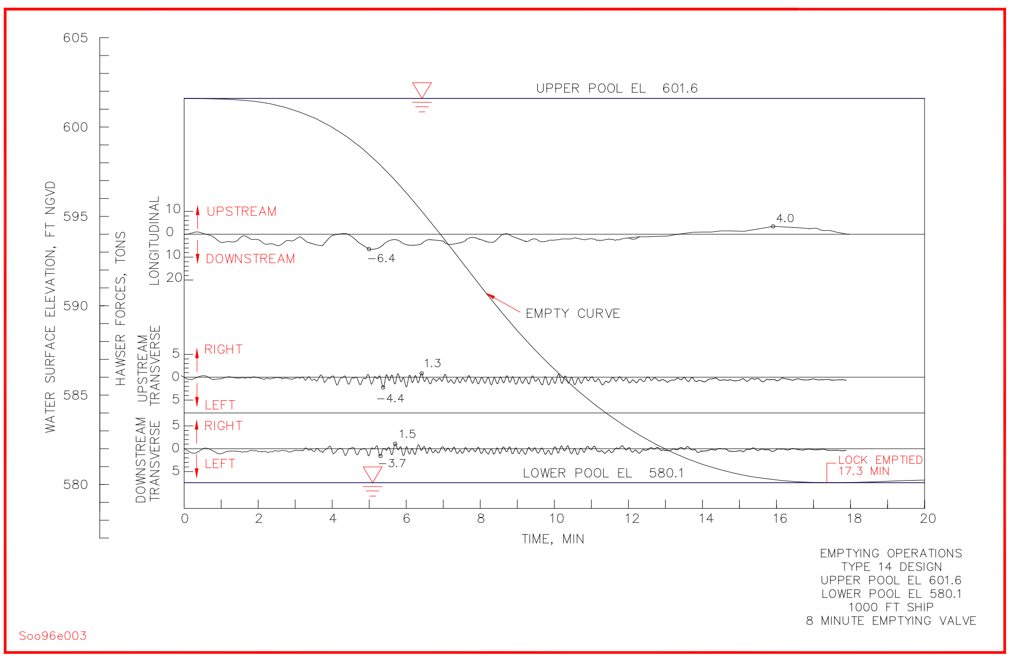


Figure 19. Typical time histories with Type 14 Chamber Design and 8-min emptying valve.

culverts through the four 12-ft high by 12-ft wide butterfly valves located on the upstream side of the upper miter sill monolith and a transition between the valves and the four 14-ft wide by 7-ft high culverts. The four large supply culverts were designated culverts 1, 2, 3, and 4 from left to right looking downstream. There were four ported culverts located in the upstream half and four ported culverts located in the downstream half of the lock chamber. The ported culverts were designated 5, 6, 7, and 8 from left to right in the downstream direction. These ported culverts had an upstream and downstream component.

The ports were located in the top of the culverts and were 2 ft by 2.5 ft. A schematic plan view of the Type 15 Chamber Design is shown in Figure 20. Figure 21 shows the lock chamber floor for the Type 15 Chamber Design looking in the downstream direction. The vertical metal bar in the center of the chamber was used for mounting the hawser force measuring equipment.

3.6.1 Steady-state pressure measurements

Steady-state pressure measurements were made to determine the pressure distribution in the filling system. Piezometers were placed throughout the intakes, culverts, and outlets. Figure 22 shows a layout for the piezometers located in the middle portion of the lock and the center distribution system. Piezometers were also placed in the ported culverts at the upstream and downstream ends and in the middle of the ported section for both the upper and lower port sections. The initial row of piezometers were located just upstream from the first row of ports and labeled 5 to 8. The next row was located in the middle of the upstream ports and was labeled 5A, 6A, 7A, and 8A. Piezometers 5B, 6B, 7B, and 8B were located just downstream from the downstream ports of the upstream ported culverts. The layout for the lower ported culverts was similar. Piezometers 5C, 6C, 7C, and 8C were located

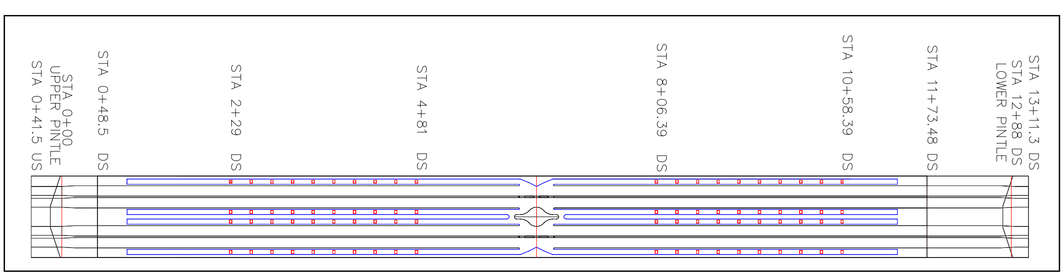


Figure 20. Plan view of Type 15 Chamber Design.

Figure 21. View of Type 15 Chamber Design lock floor (looking downstream).

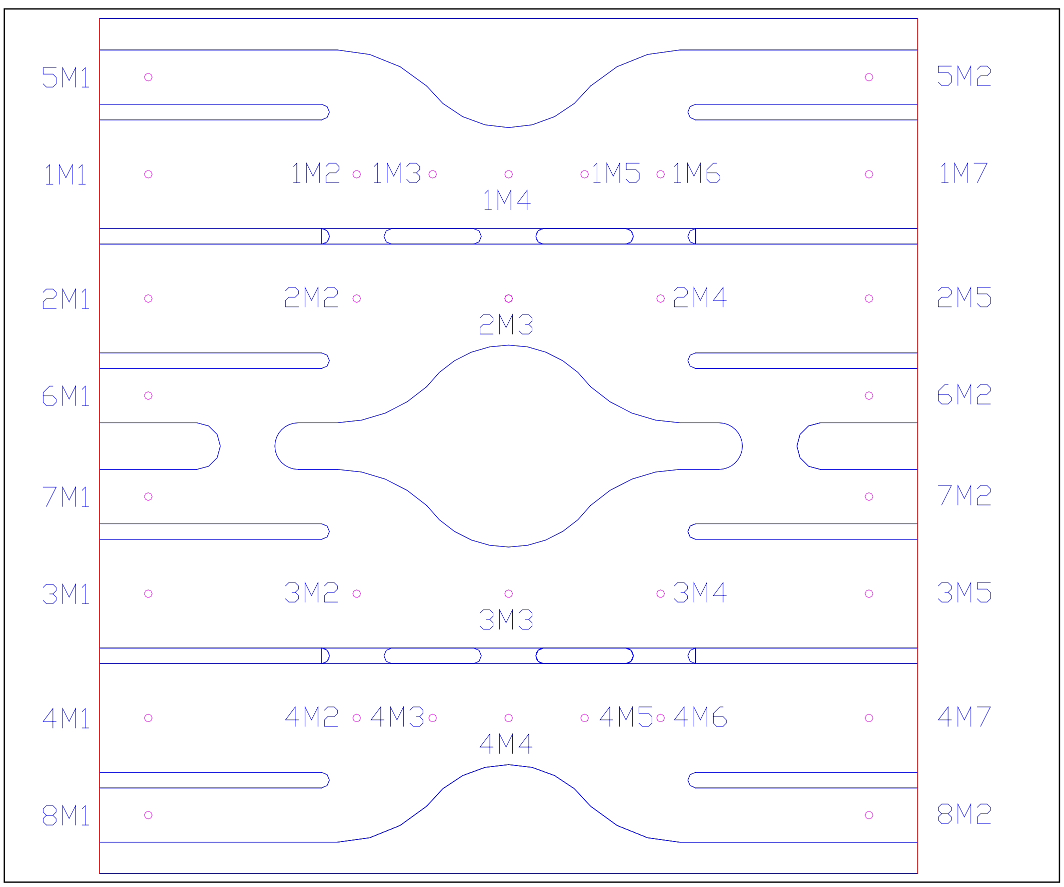


Figure 22. Piezometer layout for center distribution system in Type 15 Chamber Design.

just upstream from the upstream ports of the lower ported culverts, 5D, 6D, 7D, and 8D were located in the middle, and 5E, 6E, 7E, and 8E were located at the downstream end of the ports in the lower ported culverts. The upper pool el was 600.4 and the lower pool el was 567.5. A higher than normal lift was set for these tests to increase velocities in the culverts.

Table 3 lists piezometer readings for selected locations in the culverts. Comparison of the piezometers in the ported culverts just upstream from the middle of the lock, 5M1, 6M1, 7M1, and 8M1 to those located just downstream from the middle of the lock, 5M2, 6M2, 7M2, and 8M2 show that a higher piezometric pressure occurs in the lower ported culverts than the upper ported culverts. This is also apparent for the piezometers located in the ported sections of the upstream and downstream culverts. The pressures in the ported culvert sections indicate higher pressures in the downstream ported culverts. This indicates less head loss in these areas and results in more flow discharging from the lower ported culverts than the upper culverts. Observations of the water-surface also indicate there is more surface roughness in the lower end.

3.6.2 Hawser force measurements with Type 15 Chamber Design

Hawser force measurements were made with the ship in the chamber for selected filling and emptying operations. Figure 23 shows the ship in the chamber in preparation for these tests. Figure 24 shows time histories of the water-surface and hawser forces for a 4-min valve opening time with an upper pool el of 601.6 and a lower pool el of 580.1. The maximum longitudinal (upstream-downstream) hawser force was 22.2 tons in the upstream direction. The longitudinal hawser forces are the top time history and the transverse hawser forces are located below the longitudinal hawser forces in Figure 24 The filling curve indicated that the lock reached the upper pool el in 15.0 min. Measurements were made with valve operations of 4, 6, 8, and 10 min. The average maximum forces measured for these valve operations are plotted in Figure 25 and listed in Table 4. Figure 25 reveals that the permissible filling time for the Type 15 Chamber Design was 16.1 min. An 8-min valve opening would be required to achieve this filling time.

Time histories of water-surface and hawser forces during lock emptying are shown in Figure 26. Maximum hawser forces were well below the 15-ton limit even with this fast valve operation. The highest longitudinal forces were in the downstream direction indicating more flow discharging through the downstream ports.

Table 3. Soo Lock piezomenter readings, Type 15 Chamber Design, upper pool eL 600.4, lower pool eL 567.5.

Piezometer No.	Piezometer Rdg.	Piezometer No.	Piezometer Rdg.
5M1	572.5	5M2	577.0
6M1	573.0	6M2	576.5
7M1	574.0	7M2	576.0
8M1	574.5	8M2	573.5
1M1	582.5	1M7	587.5
2M1	582.5	2M5	587.5
3M1	582.5	3M5	587.0
4M1	582.5	4M7	587.0
1M2	585.0	1M6	587.0
2M2	585.0	2M4	587.0
3M2	584.5	3M4	586.5
4M2	584.5	4M6	586.5
5	574.0	5E	579.5
6	574.2	6E	579.2
7	573.8	7E	579.0
8	573.9	8E	580.0
5A	573.0	5D	577.2
6A	573.4	6D	577.0
7A	572.8	7D	576.8
8A	572.5	8D	577.0
5B	571.0	5C	573.0
6B	571.2	6C	573.5
7B	570.5	7C	573.0
8B	570.5	8C	573.0
1M4	586.0		
2M3	585.5		
3M3	585.5		
4M4	585.5		

Figure 23. Ship in chamber for hawser force measurements with Type 15 Chamber Design.

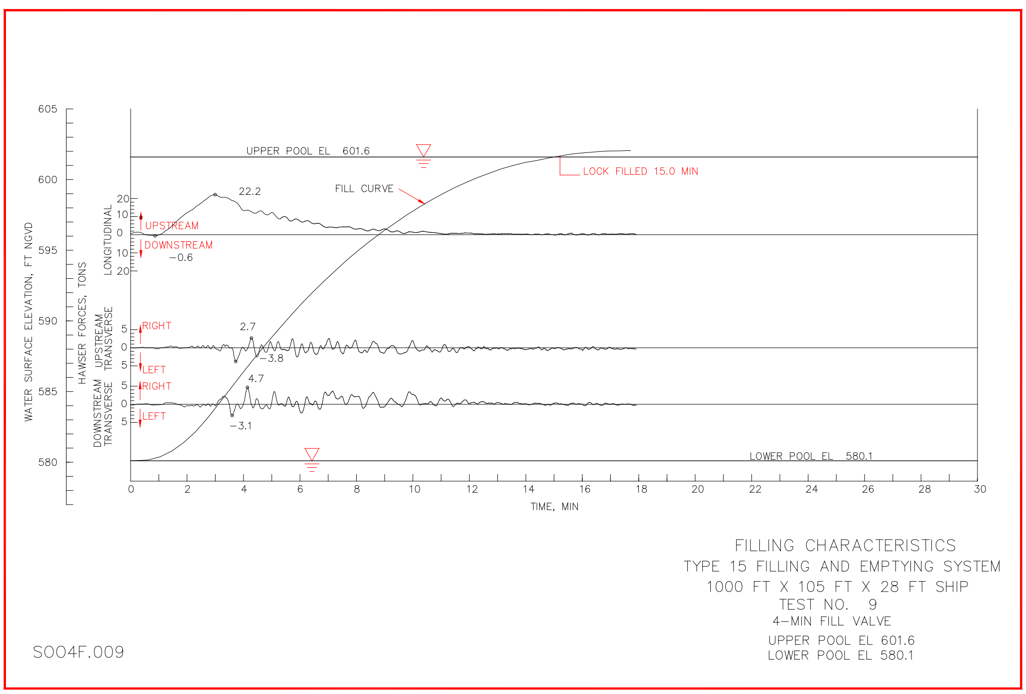


Figure 24. Time histories with Type 15 Chamber Design and 4-min valve.

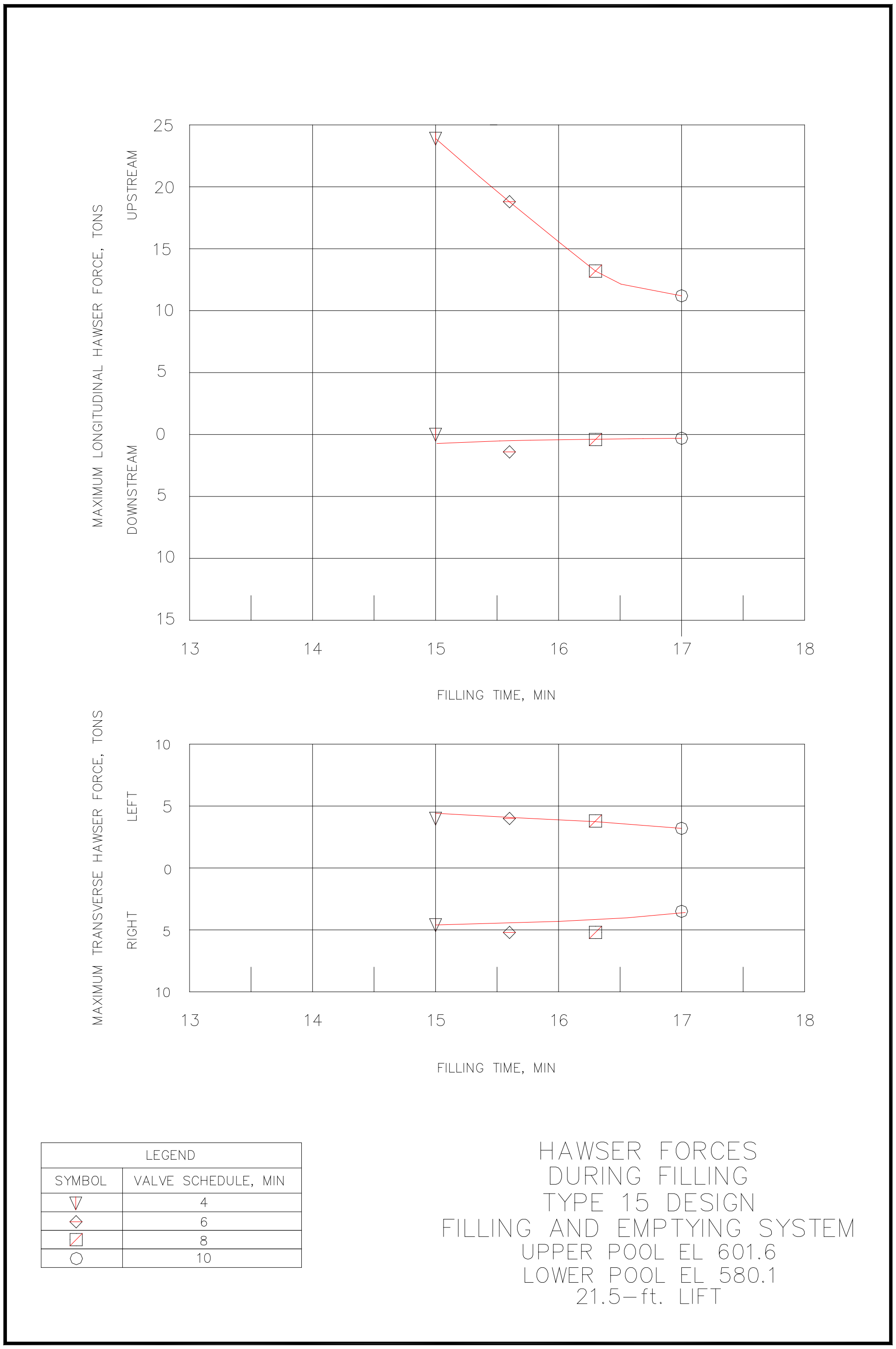


Figure 25. Average maximum hawser forces with Type 15 Chamber Design.

Table 4. Filling characteristics, Type 15 Chamber Design, 21.5-ft lift, upper pool el 601.6, lower pool el 580.1.

Valve Time (min)	Hawser Forces (Tons)						Fill Time (min)
	Longitudinal		U/S Transverse		D/S Transverse		
	U/S	D/S	Right	Left	Right	Left	
4.0	24.7	-0.6	3.5	-4.1	4.4	-3.1	14.8
	24.9	0.0	2.6	-6.7	3.2	-7.8	15.1
	22.2	0.0	2.7	-3.8	4.7	-3.1	15.0
Average	23.9	0.0	3.1	-4.0	4.6	-3.1	15.0
6.0							
	19.2	-1.6	3.4	-4.1	5.9	-4.4	15.6
	19.2	-0.9	2.7	-3.0	4.3	-2.3	15.6
	18.1	-1.8	4.2	-4.2	5.5	-5.4	15.5
Average	18.8	-1.4	3.4	-3.8	5.2	-4.0	15.6
8.0							
	13.1	-0.6	3.7	-3.9	5.9	-3.2	16.3
	13.1	-0.6	4.2	-3.9	5.9	-3.0	16.3
	13.4	0.0	3.0	-3.6	3.9	-2.7	16.3
Average	13.2	-0.4	3.6	-3.8	5.2	-3.0	16.3
10.0							
	12.0	-0.3	2.5	-3.5	4.0	-2.0	17.0
	11.0	-0.3	2.4	-2.9	4.1	-2.2	16.9
	10.5	-0.2	1.7	-3.2	2.4	-3.4	17.0
Average	11.2	-0.3	2.2	-3.2	3.5	-2.5	17.0

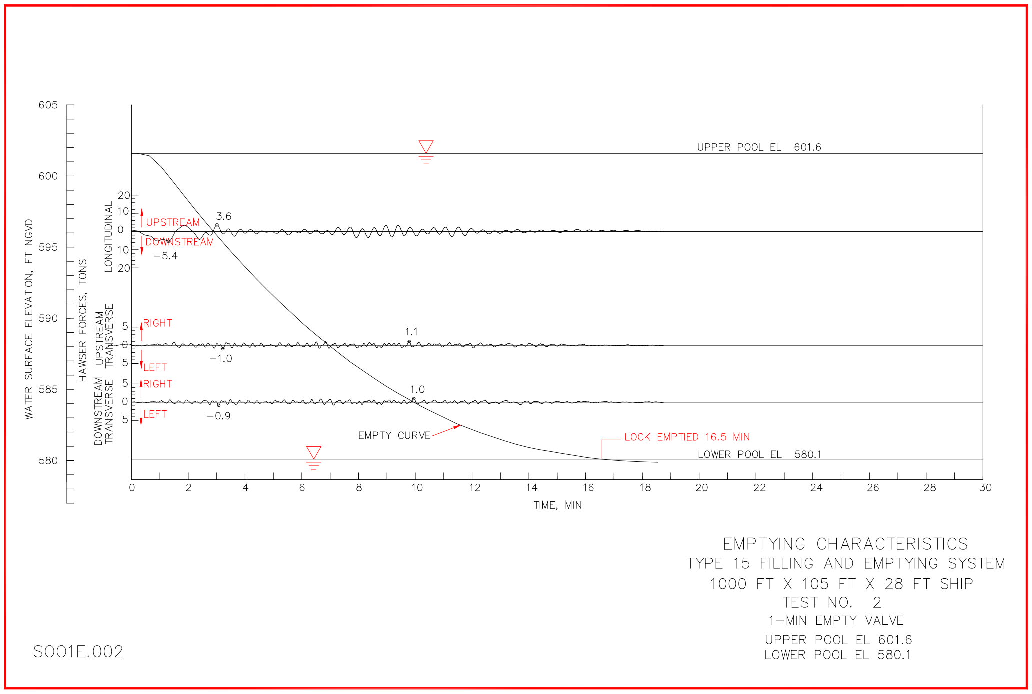


Figure 26. Time histories with Type 15 Chamber Design and 1-min emptying valve.

3.6.3 Water-surface differential measured with Type 15 Chamber Design

The water-surface differential was measured during lock filling and emptying without the ship in the chamber. This water-surface differential is also an indicator of the chamber performance during lock operations. The higher the differential, the higher the hawser forces which can be expected. Since placing the ship in and out of the chamber is quite an effort in time and funds, the water-surface differential can be used to help evaluate lock performance with modifications to the filling and emptying system. Once a suitable modification is determined, then the ship can be placed in the chamber for hawser force measurements. The water-surface differential measured with an upper pool el of 601.6, a lower pool el of 580.1, and a 4-min filling valve is shown in Figure 27. The negative sign indicates that the water-surface in the lower end of the chamber is higher than the water-surface in the upper end of the chamber at the time the difference was measured. The negative water-surface differential causes an upstream hawser force as observed in Figure 24.

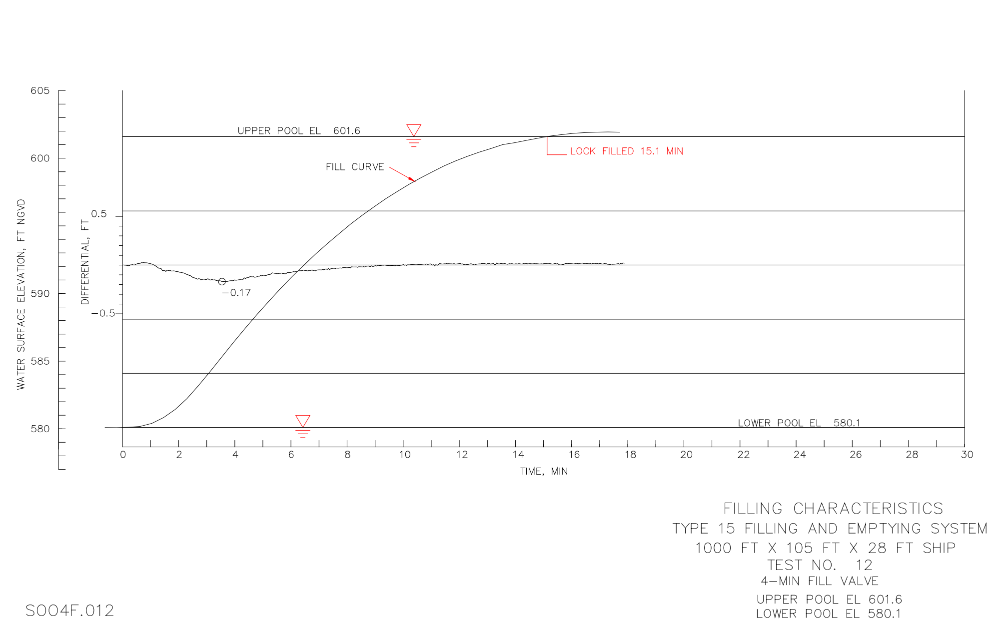


Figure 27. Time history of water-surface differential during filling with Type 15 Chamber Design and a 4-min filling valve.

3.6.4 Lock coefficient

A lock coefficient is determined to help evaluate the efficiency of the filling and emptying system. It is similar to a discharge coefficient used to determine the efficiency of a hydraulic structure to pass discharge, although the lock coefficient takes into account the unsteady flow. An equation used typically by the U.S. Army Corps of Engineers to compute the overall lock coefficient is:

$$C_L = \frac{2A_L(\sqrt{H+d} - \sqrt{d})}{A_c(T - kt_v)\sqrt{2g}} \tag{5}$$

where

A_L = area of lock chamber, ft^2
H = initial head, ft
d = overtravel, ft
A_c = area of culverts, ft^2
T = filling time, sec
k = a constant
t_v = valve opening time, sec
g = acceleration due to gravity, ft/sec^2

Refer to Davis (1989) for additional information on the development of Equation (5). The term T-k t_v is the lock filling or emptying time for the hypothetical case of instantaneous valve operation and is determined directly from the filling times associated with the various valve times. Figure 28 shows the valve time versus the filling and emptying times for the Type 15 Chamber Design. The lock coefficients computed for the conditions with a 21.5-ft lift were 0.48 during filling and 0.42 during emptying. These values are low when compared to a conventional side port system that typically has a lock coefficient during filling between 0.6 and 0.7.

3.6.5 Additional modifications considered for Type 15 Chamber Design

There were several alternatives considered to modify the filling and emptying design and improve the chamber performance. The lock operation times will not be affected significantly; however, the distribution of flow into and out of the chamber during filling and emptying could be improved. A few of the alternatives considered are listed below:

- Place a connector port in culverts 1-4.
- Modify the center section of the chamber (restrict flow in the lower ported culverts and increase flow in the upper ported culverts).
- Eliminate some lower ports and increase the number of upper ports.
- Reduce the size of lower ports and increase the size of upper ports.
- Reduce the size of downstream ported culverts (taper).

3.6.6 Row 20 ports blocked

The 4 downstream ports, row 20, of the lower ported culverts were blocked to determine the effect on the chamber water-surface during lock filling. Figure 29 shows the water-surface differential measured with the upper pool el of 601.6, lower pool el of 580.1, and a 4-min filling valve. The water-surface differential is slightly less, indicating a slight improvement in the flow distribution. With the Type 15 Chamber Design, the maximum water-surface differential with a 4-min filling valve operation was -0.17 ft and the filling time was 15.1 min. The negative sign indicates that the water-surface was higher in the lower end of the chamber. The time history of the water-surface differential shows that the water-surface differential is negative for most of the filling operation, indicating a higher water-surface in the lower portion of the lock. With row 20 ports blocked, the maximum water-surface differential was -0.15 ft and the filling time was 15.4 min for the 4-min valve operation (see Figure 29). A slight reduction in water-surface differential was observed along with a slight increase in filling time.

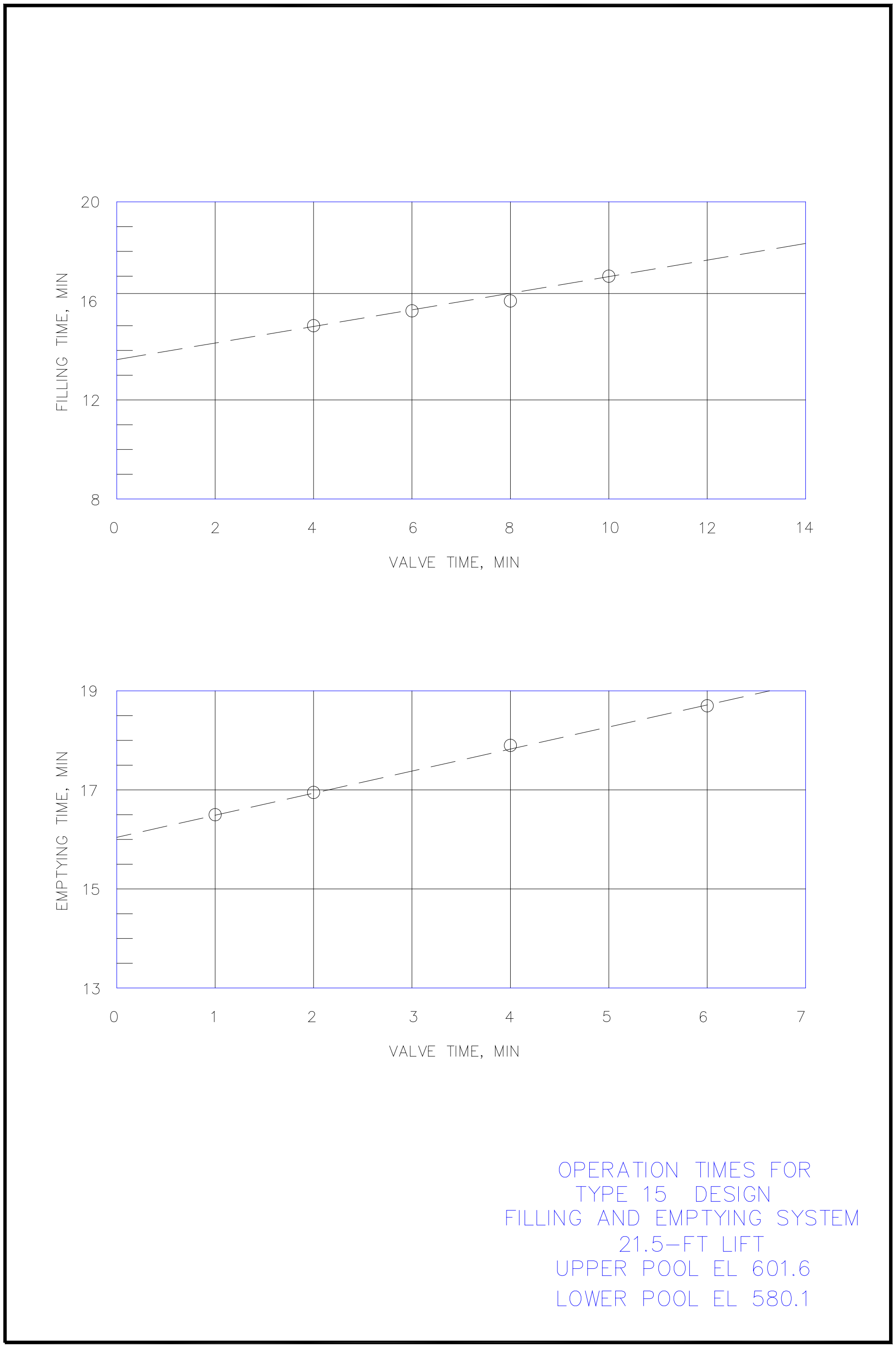


Figure 28. Valve times versus filling and emptying times with Type 15 Chamber Design.

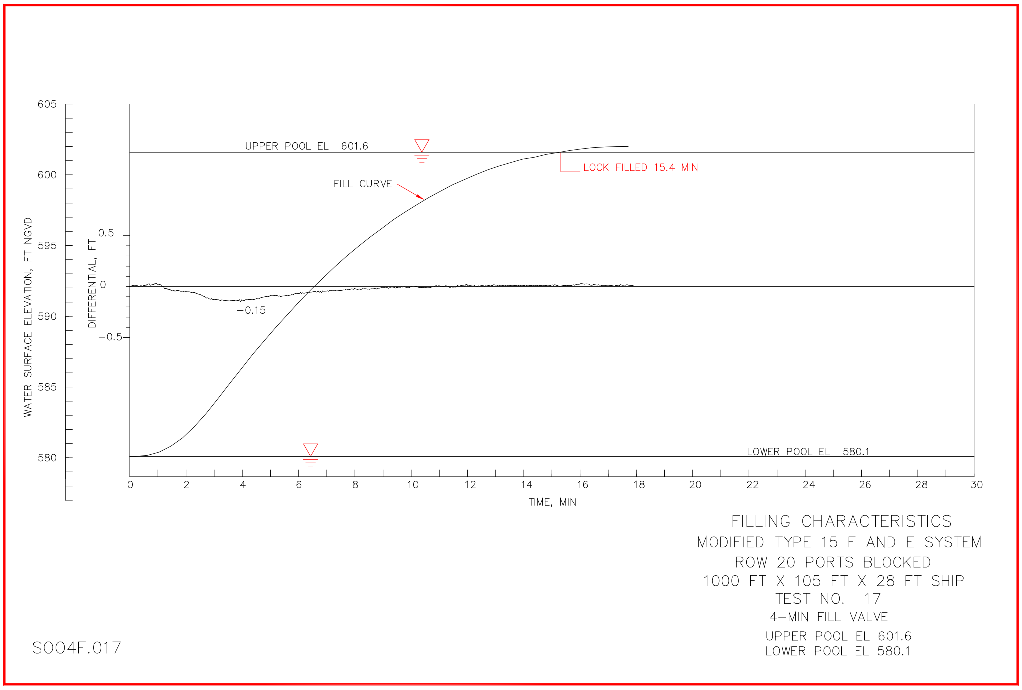


Figure 29. Time histories of water-surface and water-surface differential for a 4-min filling valve with Type 15 Chamber Design and row 20 ports blocked.

3.6.7 Row 11 ports blocked

A test was then performed with row 11 ports blocked. Row 11 is the first row in the downstream half of the chamber. The results were similar to those observed with row 20 blocked. The maximum water-surface differential was -0.15 ft and the filling time was 15.4 min for the 4-min valve operation. Time histories of water-surface and water-surface differential for a 4-min valve operation and row 11 ports blocked are shown in Figure 30.

3.6.8 Four ports added to culverts 1-4

Four circular ports (slightly larger than 5 ft in diameter) were added to culverts 1-4, the supply culverts, at a distance of 229 ft from the upper pintle. This is the same distance downstream as the row 1 ports in culverts 5-8. The circular area was intended to approximate the area of the 2 ft by 2.5 ft rectangular ports in the Type 15 Chamber Design. The intent was to introduce more discharge in the upper end of the chamber by releasing some flow from the supply culverts. The maximum water-surface differential with this modification was -0.18 ft and the filling time was 14.5 min, as shown in Figure 31. A slight increase in water-surface differential was observed and the filling time was less than the previous modifications. The water-surface differential data still indicated a higher water-surface in the

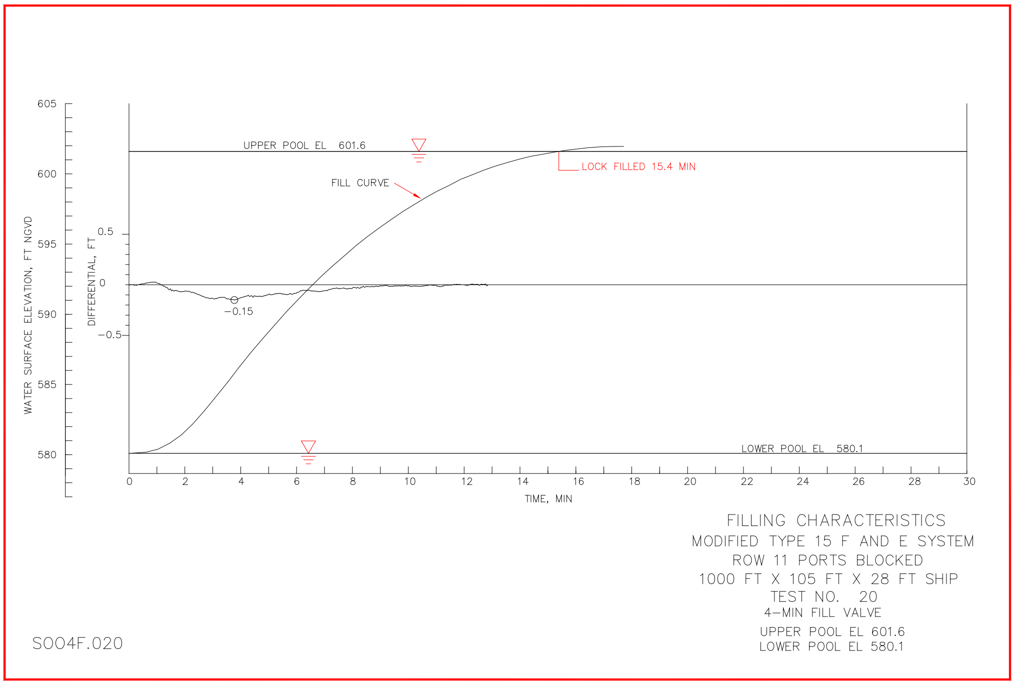


Figure 30. Time histories of water-surface and water-surface differential for a 4-min filling valve operation with the Type 15 Chamber and row 11 ports blocked.

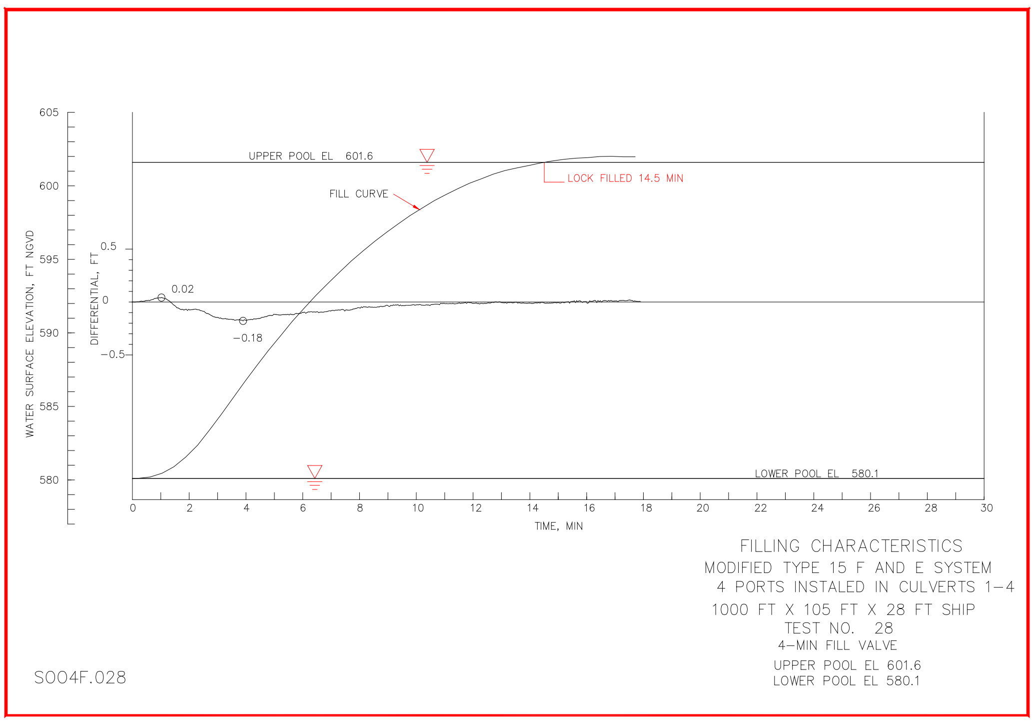


Figure 31. Time histories of water-surface and water-surface differential for 4-min filling valve operation with modified Type 15 Chamber Design (4 ports added in culverts 1-4).

lower end of the lock during the filling operation. Evidently, the additional flow introduced in the upper end of the chamber through the additional ports in row 1 was reducing the flow to the upper ports in culverts 5-8. This reduction in flow to the upper ports in culverts 5-8 resulted in the higher water-surface in the lower half of the lock.

3.6.9 4 ports added to culverts 1-4 and row 11 ports blocked

Row 11 ports were then blocked in addition to the 4 circular ports added to culverts 1-4. The maximum water-surface differential measured with a 4-min filling valve was -0.15 and the filling time was 14.7 min (see Figure 32). This design showed more potential so ports identical to those in culverts 5-8 were installed in the model to replace the temporary circular ports.

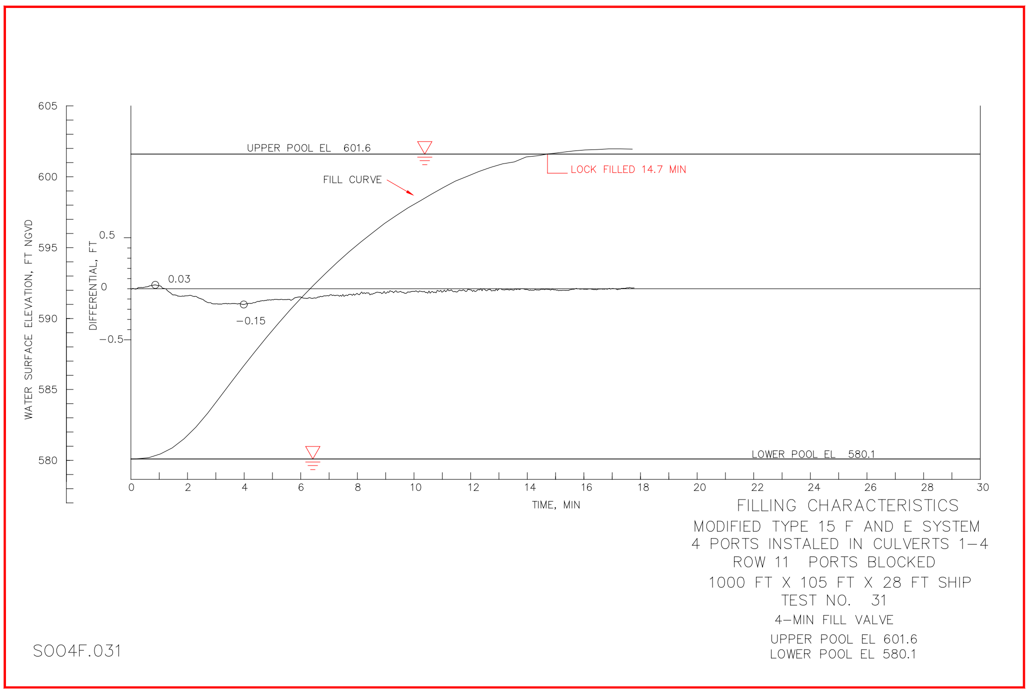
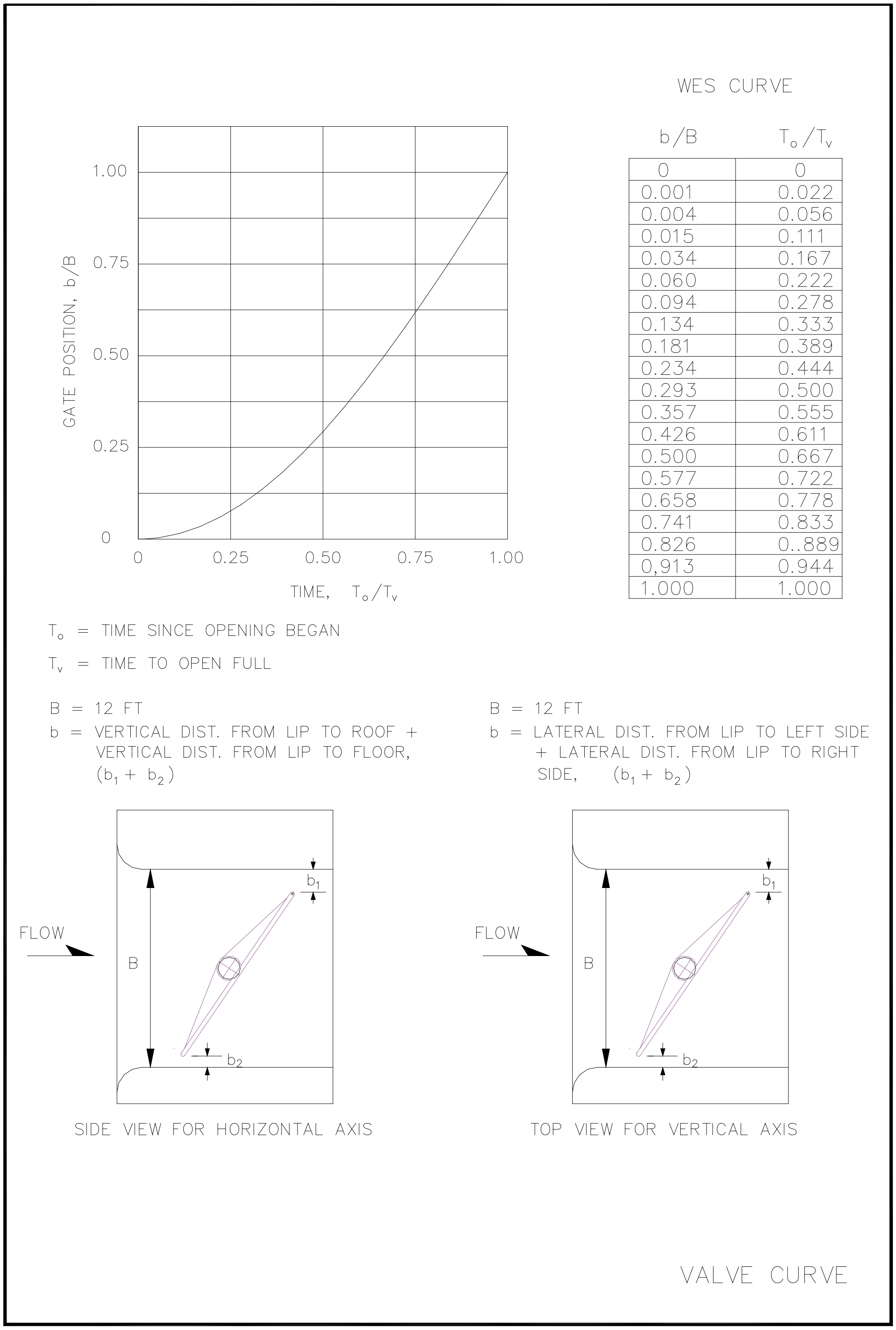


Figure 32. Time histories of water-surface and water-surface differential for 4-min filling valve operation with modified Type 15 Design (4 ports added in culverts 1-4 and row 11 ports blocked).

3.7 Filling valve modification

In all previous model experiments with the New Soo Lock filling and emptying system, the axis of the filling and emptying butterfly valves were mounted horizontally. This is shown in Figure 33 for the schematic on the left side of the figure. As shown in Figure 33, the valve is not shaped symmetrically so there is a slight difference in the flow on each side of the



b/B	T_o/T_v
0	0
0.001	0.022
0.004	0.056
0.015	0.111
0.034	0.167
0.060	0.222
0.094	0.278
0.134	0.333
0.181	0.389
0.234	0.444
0.293	0.500
0.357	0.555
0.426	0.611
0.500	0.667
0.577	0.722
0.658	0.778
0.741	0.833
0.826	0..889
0,913	0.944
1.000	1.000

Figure 33. Filling valve orientation used in Soo Lock model experiments.

valve. A decision was made to change the axis of the valve from a horizontal mount to a vertical mount. The valve machinery was more adaptable to a vertically mounted axis. The valves were installed initially to open in the clockwise direction (looking in plan view). This change to the valves was made along with the changes to the culvert ports described below. Intake conditions will be discussed in a subsequent section of the report.

3.8 Type 16 Chamber Design

Two rows of ports were added to culverts 1-4 at the same distance downstream from the upper pintle as rows 1 and 2 with the Type 15 Chamber Design. The port shape was the same, 2.0 ft by 2.5 ft by 3 thick, as the Type 15 Chamber Design. The ports in row 11 were also blocked. Since these changes were permanent, this design was designated the Type 16 Chamber Design. This design contained 48 ports (57%) in the upper half of the chamber and 36 ports (43%) in the lower half of the chamber. Hawser force measurements were made for 4-, 6-, and 8-min filling valve operations. Typical time histories of hawser forces and water-surface elevation are shown in Figure 34 for the 4-min filling valve operation. The maximum longitudinal hawser force was 29.8 tons and occurred around 4 min into the filling operation. This force was considerably higher than the 15 ton limit for the permissible filling time. The filling time was 13.9 min. Table 5 provides a summary of filling times and hawser forces obtained with the Type 16 Chamber Design.

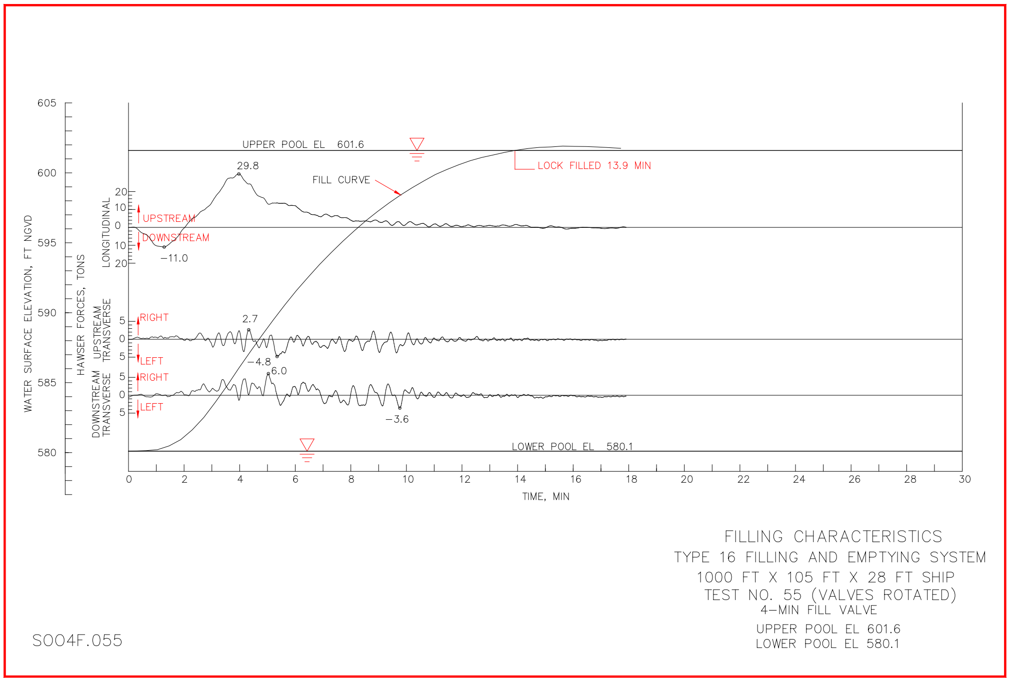


Figure 34. Time histories of water-surface and hawser forces for 4-min filling valve operation with Type 16 Chamber Design (8 ports added in culverts 1-4 and row 11 ports blocked).

Table 5. Filling characteristics, Type 16 Chamber Design, 21.5-ft lift, upper pool el 601.6, lower pool el 580.1.

Valve Time (min)	Hawser Force (Tons)						Fill Time (min)
	Longitudinal		U/S Transverse		D/S Transverse		
	U/S	D/S	Right	Left	Right	Left	
4.0	29.9	-10.7	2.1	-4.2	5.4	-4.6	14.0
	29.8	-11.0	2.7	-4.8	5.0	-3.6	13.9
	30.7	-11.4	3.1	-5.3	4.1	-2.3	13.9
Average	30.1	-11.0	2.3	-4.8	4.8	-3.5	13.9
6.0							
	22.5	-8.5	3.6	-4.1	4.9	-3.6	14.8
	21.2	-7.2	2.9	-3.6	3.9	-3.5	14.9
	21.8	-7.3	1.8	-4.0	4.7	-2.0	14.8
Average	21.8	-7.7	2.7	-3.9	4.5	-3.0	14.8
8.0							
	19.4	-5.3	3.6	-3.9	5.9	-2.2	15.5
	18.7	-5.6	2.3	-4.2	5.1	-3.8	15.3
Average	19.0	-5.5	3.0	-4.1	5.5	-3.0	15.4

Typical time histories of water-surface and hawser forces with the 8-min valve are shown in Figure 35. The maximum longitudinal hawser force was 18.7 tons, which was still higher than desired. The filling time was 15.3 min. The results showed that a prolonged upstream hawser force occurred during the filling operation which indicated a higher water-surface in the lower half of the chamber. The permissible filling time extrapolated from the tests with the Type 16 Chamber Design was 16.3 min. This was determined by plotting the average maximum of the hawser forces and filling times determined from tests conducted with 4-, 6-, and 8-min valve

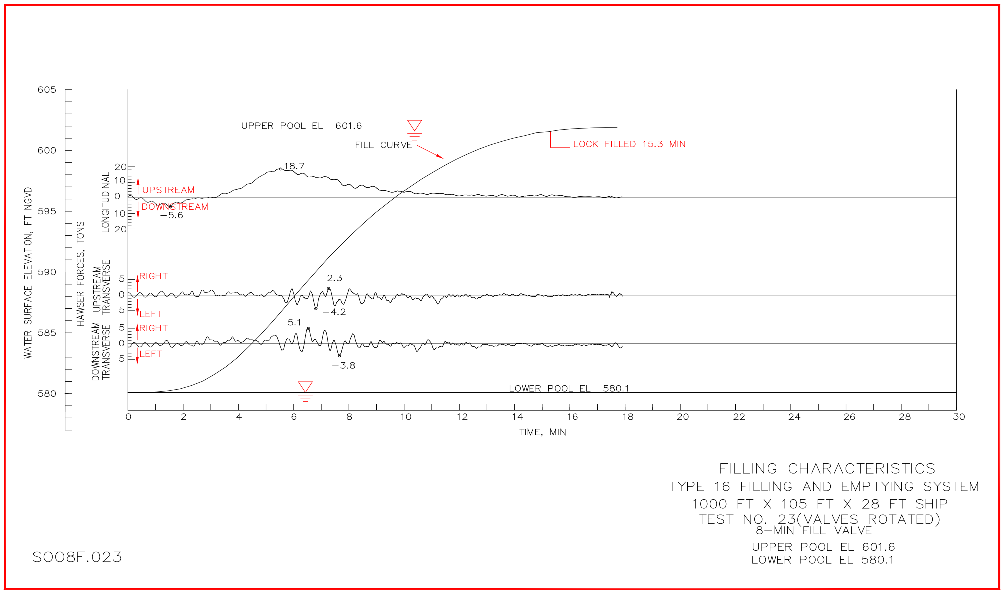


Figure 35. Typical time histories of water-surface and hawser forces for 8-min filling valve operation with Type 16 Design.

operations. Figure 36 shows plots of the average maximum hawser forces for the Type 15-17 Chamber Designs. The permissible filling time for the Type 15 Chamber Design was 16.1 min. A slower valve operation was required with the Type 16 Design to maintain hawser forces of 15 tons or less compared to the Type 15 Chamber Design.

Hawser forces were measured next with the Type 16 Chamber Design and a 1-min emptying valve. Typical time histories are shown in Figure 37. The maximum hawser forces were well below the 15 ton limit and the lock emptied in 14.4 min. This was an improvement in emptying time compared to the Type 15 Chamber Design, which emptied in 16.5 min with a 1-min valve operation.

3.9 Type 17 Chamber Design

The Type 17 Chamber Design included the modifications in the Type 16 Chamber Design along with blocking the ports in row 20. The upper chamber contained 48 ports (60%) and the lower chamber contained 32 ports (40%). Typical time histories of hawser forces and water-surface elevation are shown in Figure 38 for the 4-min filling valve operation. The maximum longitudinal hawser force was 25.9 tons and occurred around 4 min into the filling operation. This force was still higher than the 15 ton limit for the permissible filling time. The filling time was 14.1 min. Hawser force measurements were then measured for 6-, 8-, and 10-min valve operations.

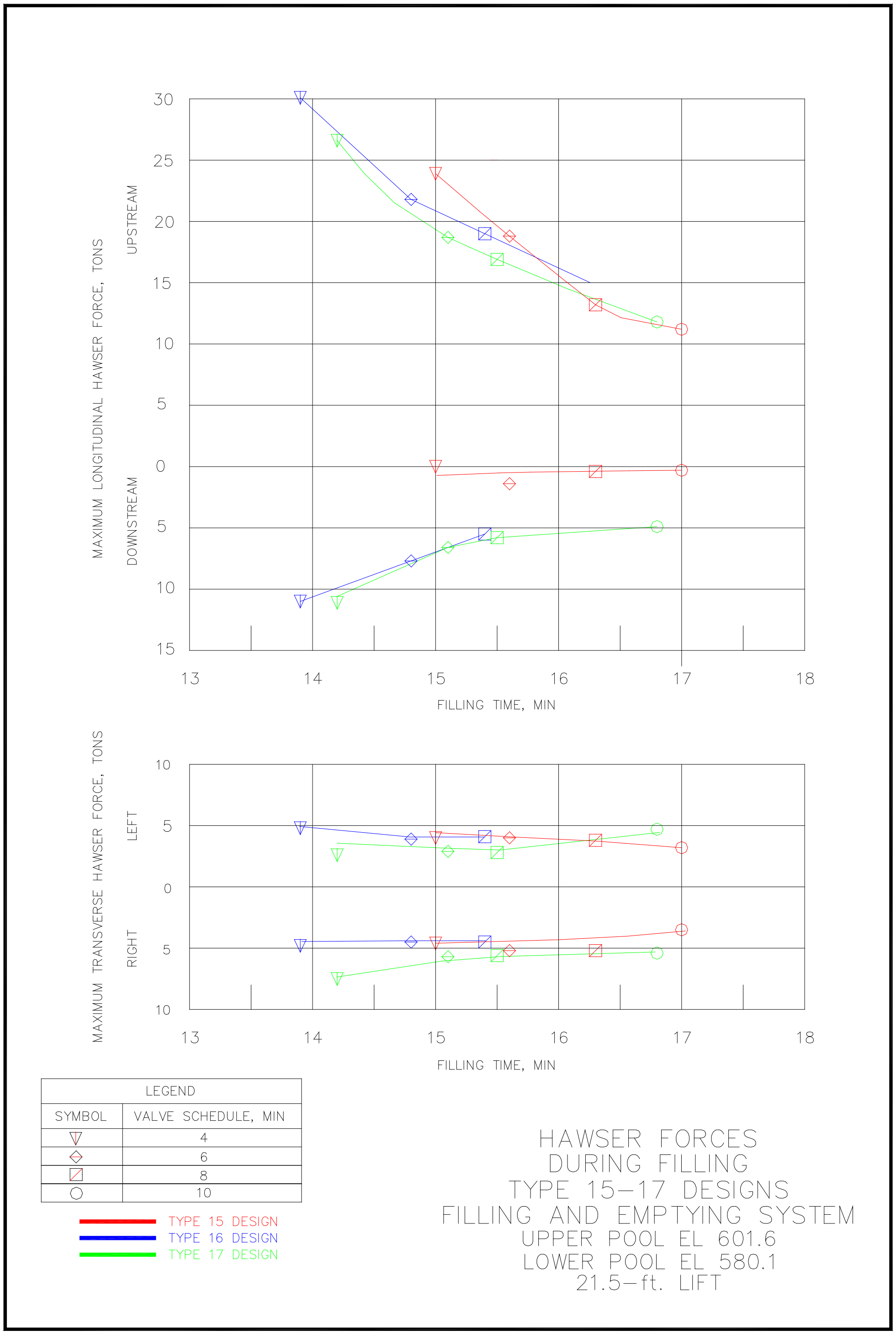


Figure 36. Comparison of average maximum hawser forces determined for the Type 15-17 Designs.

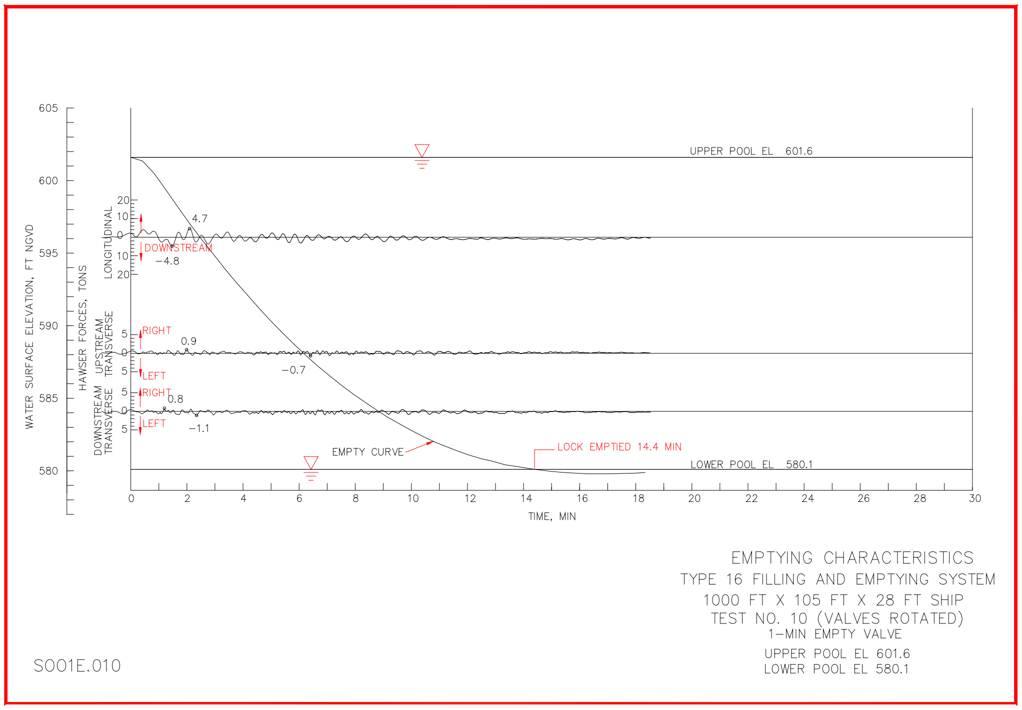


Figure 37. Typical time histories of water-surface and hawser forces for 1-min emptying valve operation with Type 16 Chamber Design.

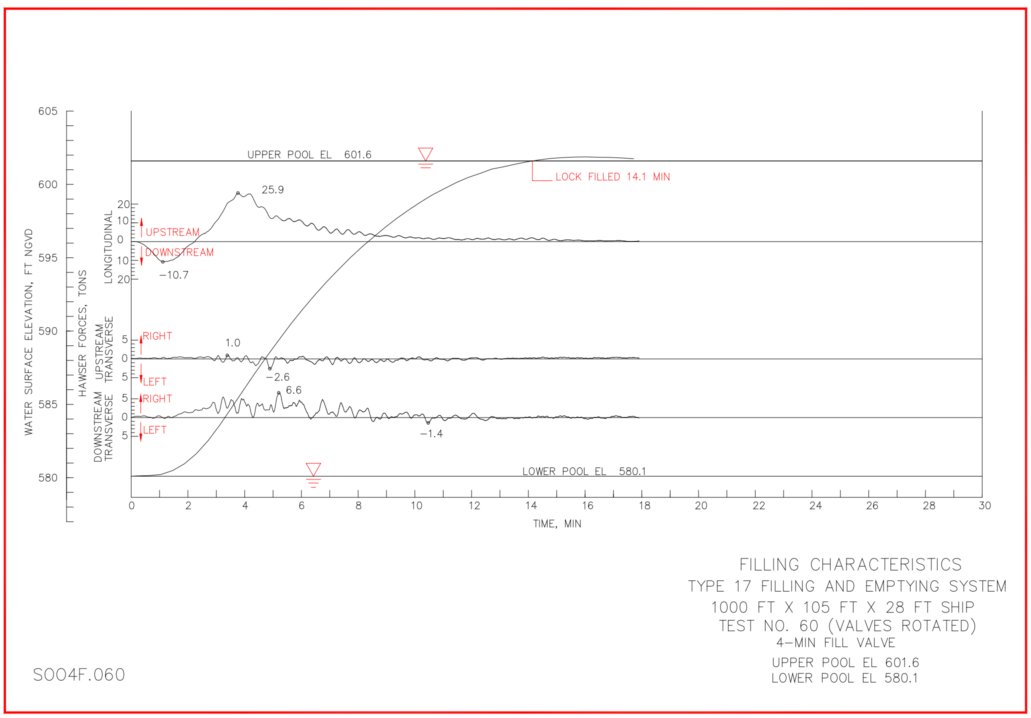


Figure 38. Typical time histories of water-surface and hawser forces for 4-min filling valve operation with Type 17 Chamber Design.

Typical time histories of water-surface and hawser forces with the 10-min filling valve operation are shown in Figure 39. The maximum longitudinal hawser force was 11.8 tons and the filling time was 16.8 min. The hawser forces for this valve operation were under the 15 ton limit. The permissible filling time determined from the hawser force measurements shown in Figure 36 was 15.9 min, slightly faster than the Type 15 Chamber Design. Table 6 provides a summary of filling times and hawser forces obtained with the Type 17 Chamber Design.

3.9.1 Intake vortex formation clockwise valve operation

Observations of the approach flow conditions with the valve axis in the vertical position and the valve opening in the clockwise direction revealed vortices forming on the right side of the approach during lock filling. Type 4 vortices were observed during 4-, 6-, 8-, and 10-min valve operations. The vortex strength classification used for these experiments is shown in Figure 6. The strong vortices always formed on the right side of the approach. Vortices stronger than Type 3 that form in a 1:25-scale model indicate a potential for strong vortex formation in the prototype. These vortices were stronger than observed when the axis of the valve was horizontal. The flat side of the valve was located on the right side (looking downstream) when the valve was fully open, which meant that this side of the valve probably had slightly more flow entering the intake on this side.

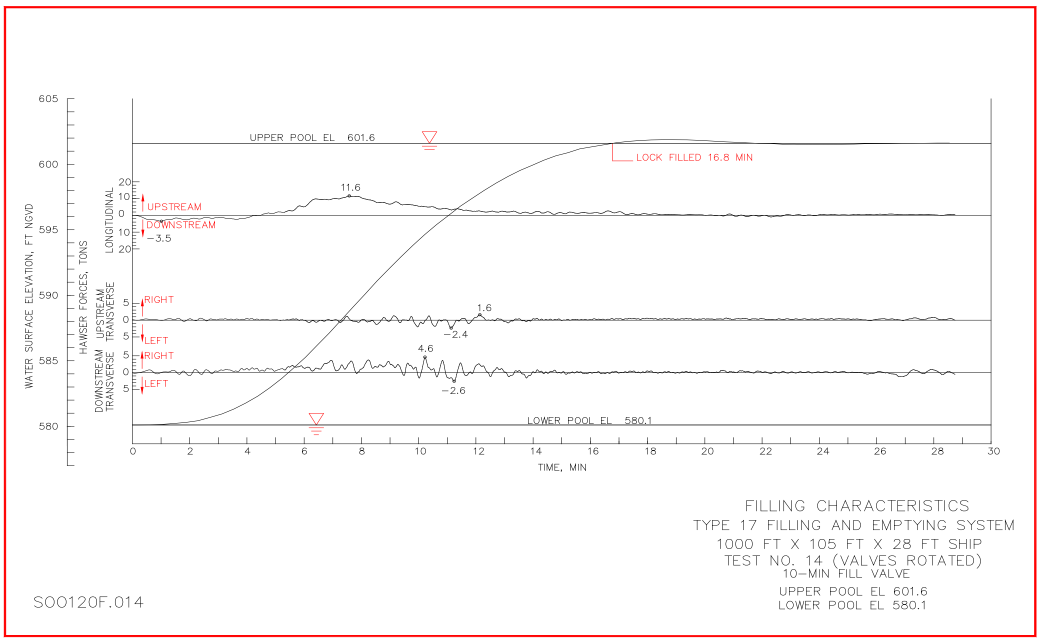


Figure 39. Typical time histories of water-surface and hawser forces for 10-min filling valve operation with Type 17 Chamber Design.

Table 6. Filling characteristics, Type 17 Chamber Design, 21.5-ft lift, upper pool el 601.6, lower pool el 580.1.

Valve Time (min)	Hawser Force (Tons)						Fill Time (min)
	Longitudinal		U/S Transverse		D/S Transverse		
	U/S	D/S	Right	Left	Right	Left	
4.0	26.3	-11.4			8.4	-2.8	14.2
	25.9	-10.7	1.0	-2.6	6.6	-1.4	14.1
Average	26.6	-11.1	1.0	-2.6	7.5	-2.1	14.2
6.0							
	19.3	-6.5			6.2	-1.4	15.0
	18.0	-6.7	1.5	-1.9	5.2	-4.3	15.1
Average	18.7	-6.6	1.5	-1.9	5.7	-2.9	15.1
8.0							
	17.5	-5.8	1.1	-1.8	5.1	-2.7	15.4
	16.4	-5.8	1.7	-2.7	6.1	-2.8	15.5
Average	16.9	-5.8	1.4	-2.3	5.6	-2.8	15.5
10.0							
	11.8	-3.5	1.6	-2.4	4.6	-2.6	16.8
	11.8	-7.4	3.6	-3.6	8.2	-6.8	16.8
Average	11.8	-4.9	2.6	-3.0	5.4	-4.7	16.8

3.9.2 Intake vortex formation counter clockwise valve operation

Tests were conducted next opening the valve in a counter clockwise direction to see if the opening direction affected the vortex formation. With this valve operation, the flat side of the valve would be on the left side when the valve was fully open. The vortex strength was not affected by opening the valve in a counter clockwise direction. Type 4 vortices were observed for 4- and 8-min valve operations. Structural modifications were then considered to reduce the strength of the vortices.

3.9.3 Vortex tests with 60-ft roof extension

A thin flat plate was extended upstream from the face of the valves with the top of the plate at the same elevation as the upper miter sill (el 563.4). The length of the plate for the initial tests was 60 ft. The first couple of tests with various valve operations showed that the vortex strength was reduced but after a complete set of tests with 4-, 6-, 8-, and 10-min valve operations was completed, a Type 4 vortex formed during these valve operations. Typically, three tests are conducted for each valve operation. This long extension was concentrating flow between the upper emergency gate sill and the roof extension. Tests were conducted next with the roof extension shortened.

3.9.4 Vortex tests with 25- and 15-ft roof extensions

A 25-ft long roof extension was evaluated for 4- and 10-min filling valve operations. A Type 2 vortex was the strongest that was observed during these tests. The length was reduced to 15 ft and approach flows were observed for 4-, 8-, and 10-min valve operations. A Type 3 vortex occurred in 1 of the 3 tests conducted with the 4-min valve operation. The strongest observed in the other tests was a Type 2. Approach flow conditions were considered acceptable with the 15- and 25-ft roof extensions.

3.9.5 Vortex tests with 10- and 5-ft roof extensions

A 10-ft roof extension was tested next for 4-, 8-, and 10-min valve operations. Type 4 vortices were observed during the 4- and 8-min valve operations. The 5-ft long roof extension was tested next. Strong Type 3 vortices were observed with 4- and 8-min valve operations. It appeared that the vortices would become stronger than Type 3 but the strength was reduced due to surface roughness that occurred with the 5-ft roof extension. Due to the large surface roughness and strong Type 3 vortices, the 5-ft roof extension was considered unacceptable.

3.10 Type 15 Chamber Design; non-standard valve operations

The Type 15 Chamber Design was considered to be the best performing system of those evaluated. Additional experiments were performed to further evaluate the performance of the Type 15 Chamber Design for non-standard valve operations. Non-standard valve operations may be necessary for maintenance or a malfunctioning valve. All tests were performed with a 21.5-ft lift. The upper pool el was 601.6 and the lower pool el was 580.1.

3.10.1 Valve description

The proposed valves for the New Soo Lock are 12-ft by 12-ft butterfly valves. Four valves mounted on the upstream side of the upper miter gate monolith are used for lock filling and four valves mounted on the downstream side of the lower miter gate monolith are used for lock emptying. The filling valves are numbered 1 to 4 looking downstream and the emptying valves are numbered 5 to 8 also looking downstream. The axis of the valve was mounted vertically, as shown in the top view in Figure 33 (lower right), which also includes the valve opening curve. The valves opened in a counter clockwise direction.

3.10.2 Three valves operating

Tests were conducted with valves 1, 2, and 3 operating and valve 4 closed. Time histories of water-surface and hawser forces were measured during each test. Longitudinal hawser forces were measured to observe the upstream-downstream movement of the ship in the chamber and transverse hawser forces were measured to observe the side to side movement at both ends of the chamber. A typical time history with valves 1, 2, and 3 operating is shown in Figure 40.

Figure 40 shows that the lock filled in 18.2 min and the maximum hawser force measured was an upstream longitudinal hawser force of 14.6 tons that occurred nearly 5 min into the filling operation. The upstream longitudinal force was dominant during the filling operation. This indicates that more flow was being discharged from the lower ports causing a slope in the water-surface with a higher water level in the lower end of the chamber. The transverse forces showed that the ship was pushed to the right side of the chamber during filling. Valves 1 and 2 feed culverts located on the left side of the chamber and together, they discharge more than the culvert being fed by valve 3, which was located on the right side of the chamber. This caused a transverse slope with the water-surface on the left side of the channel being slightly higher than the water-surface on the right side of the channel.

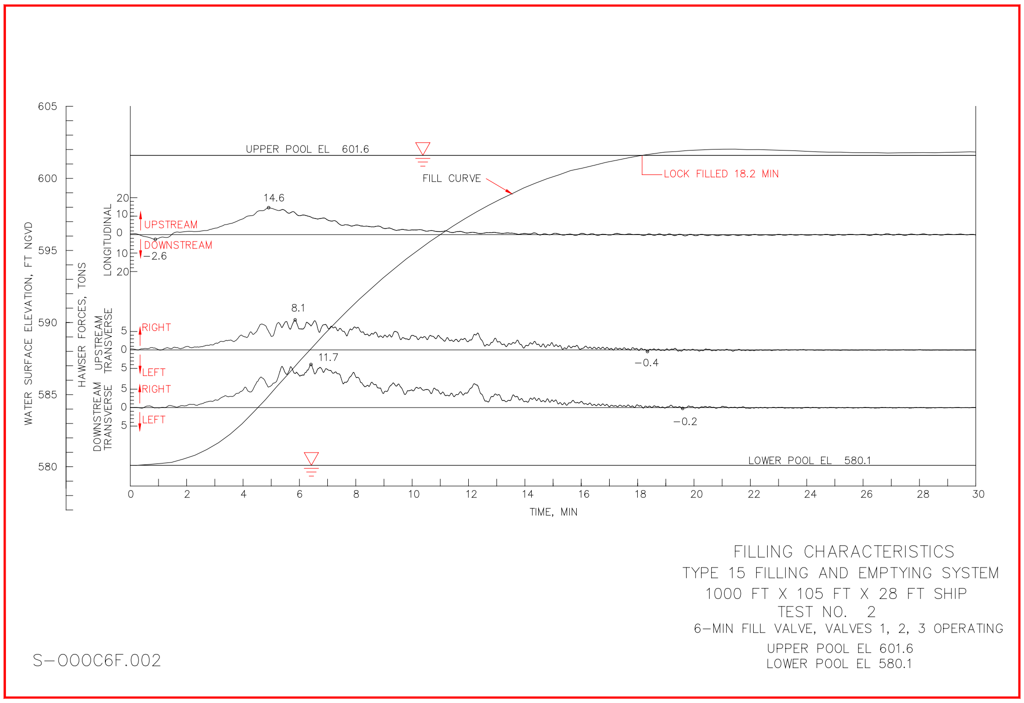


Figure 40. Typical time histories of water-surface and hawser forces during a 6-min filling valve operation with valves 1, 2, and 3 operating and Type 15 Chamber Design.

Tests were performed with 2-, 4-, 6- and 8-min valve operations to determine the filling times and hawser forces for each of these valve speeds. The average values of the filling times and hawser forces determined for the tests with valves 1, 2, and 3 operating are shown in Figure 41 and listed in Table 7. The Corps guidance for maximum hawser forces allowed for a ship of this size (1,000 ft long by 105 ft wide with a 28-ft draft) is 15 tons. Figure 41 shows that this 15 ton limit occurs on the upstream longitudinal hawser force with a filling time of 18.3 min and a valve speed slightly slower than 6 min. The transverse hawser forces were all less than 10 tons. A plot of filling time versus valve time for valves 1, 2, and 3 operating is shown in Figure 42. The plot shows that with valves 1, 2, and 3 operating, a filling time of 18.3 min is achieved with a valve time of 6.1 min.

3.10.3 Valves 1, 2, and 4 operating

Similar tests were conducted with valves 1, 2, and 4 operating. Typical time histories are shown in Figure 43 for a 6-min valve operation. The maximum longitudinal hawser force was 14.3 tons and occurred in the upstream direction around 5 min into the filling operation. The transverse hawser forces were less than the longitudinal forces and indicated that the ship was pushed to the right side of the chamber, as was noticed with

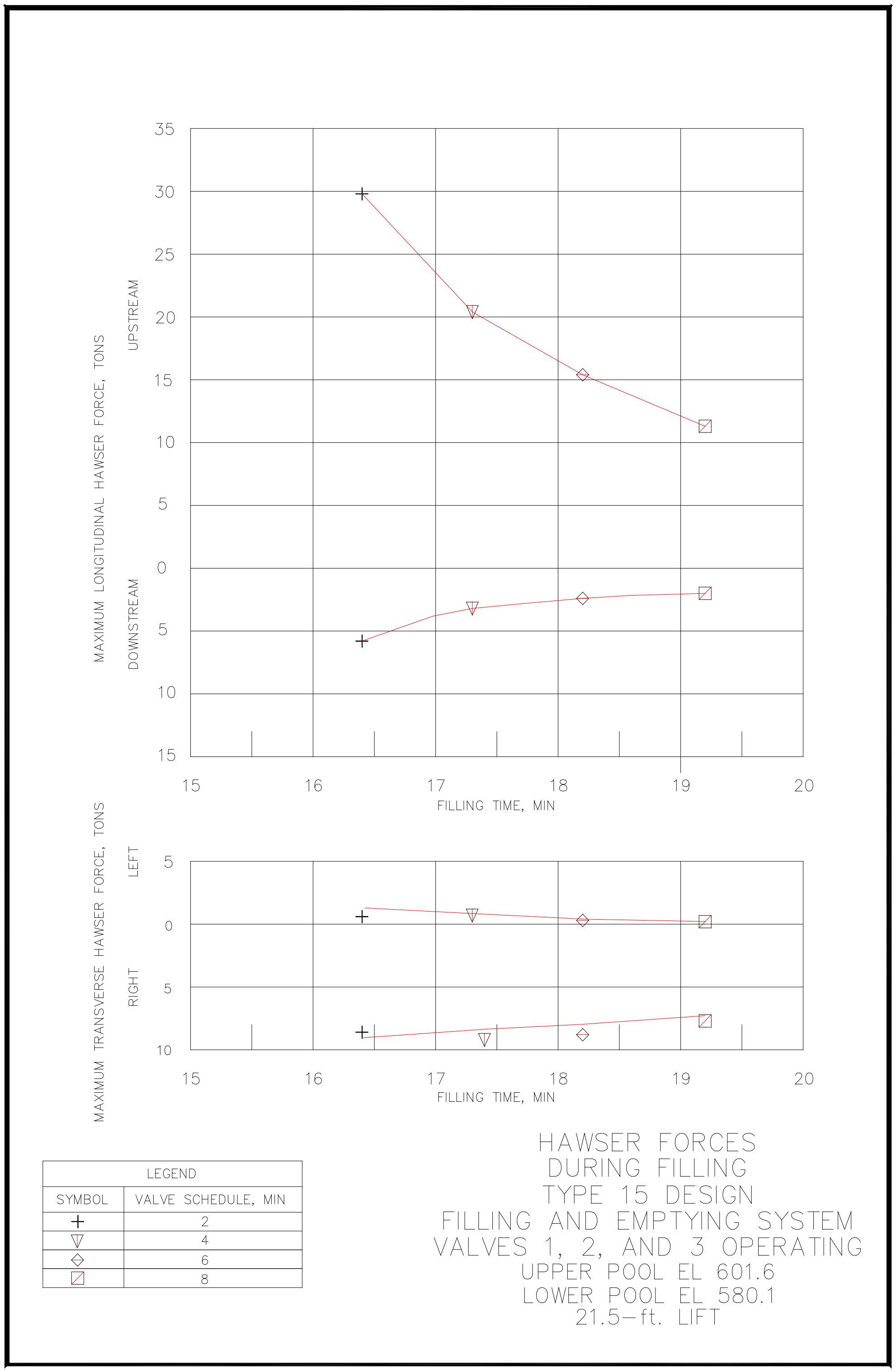


Figure 41. Average maximum hawser forces during filling with Type 15 Chamber Design for valves 1, 2, and 3 operating.

Table 7. Filling characteristics, Type 15 filling and emptying system, valves 1, 2, and 3 operating, 21.5-ft lift, upper pool el 601.6, lower pool el 580.1.

Valve Time (min)	Hawser Forces (Tons)						Fill Time (min)
	Longitudinal		U/S Transverse		D/S Transverse		
	U/S	D/S	Right	Left	Right	Left	
2.0	30.8	-5.6	7.0				16.5
	29.2	-6.1	10.8	-0.7	11.8	-0.3	16.3
	30.5	-5.8	8.1	-0.4	5.4	-0.1	16.5
Average	30.2	5.8	8.6	-0.6	8.6	-0.1	16.4
4.0							
	21.5	-3.2	8.2	-0.8		-1.0	17.3
	19.3	-3.3	9.9	-0.6	12.5	-0.2	17.4
	20.5	-3.2	8.2	-0	6.0	0	17.3
Average	20.4	-3.2	8.8	-0.7	9.2	-0.6	17.3
6.0							
	15.4	-2.3	8.2	-0	18.2	-0	18.3
	14.6	-2.6	8.1	-0.4	11.7	-0.2	18.2
	15.4	-2.4	9.5	-0.3	5.8	-0.1	18.1
Average	15.1	-2.4	8.4	-0.3	11.9	-0.3	18.2
8.0							
	11.1	-2.3	8.7	-0.3	11.2	-0.3	19.4
	11.4	-1.6	7.8	-0.3	10.3	-0.3	19.2
	11.5	-2.1	7.7	-0	5.0	-0.1	19.2
Average	11.3	-2.0	8.1	-0.2	8.9	-0.2	19.2

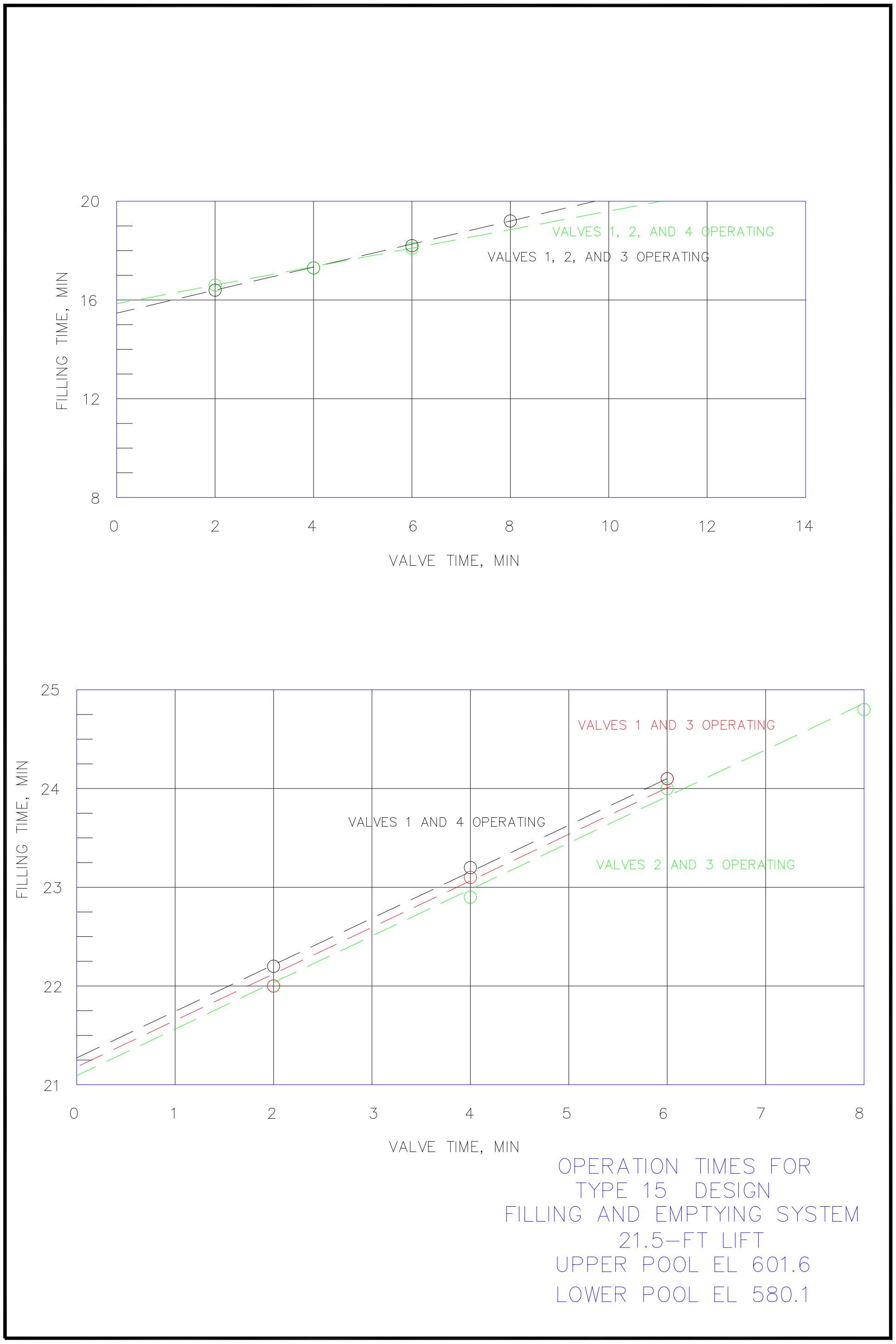


Figure 42. Filling time versus valve time with Type 15 Chamber Design for 3 and 2 valves operating.

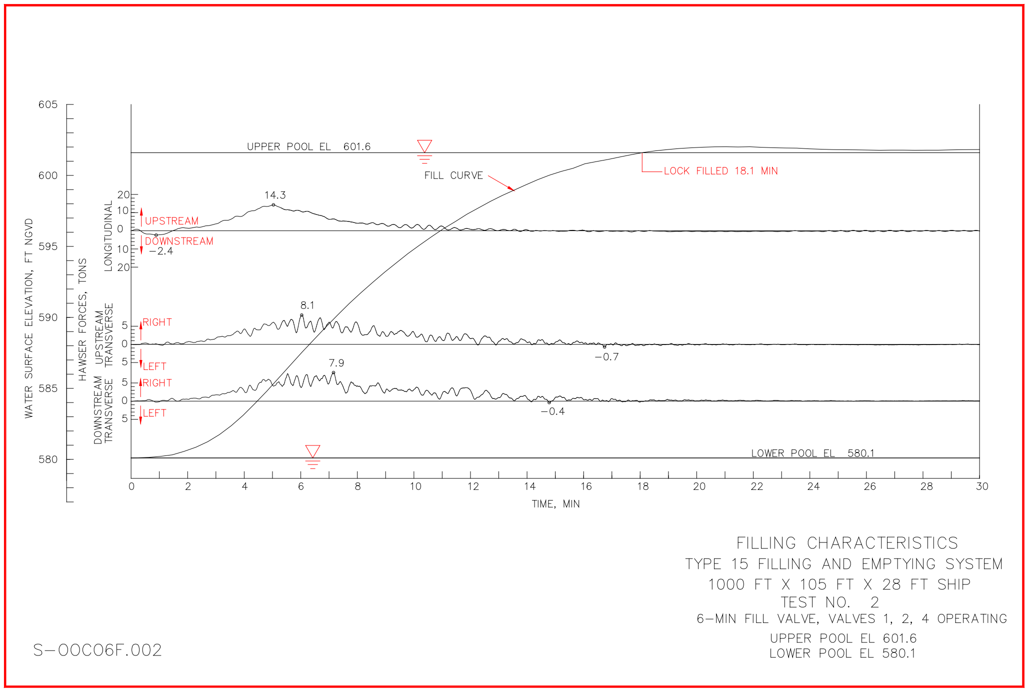


Figure 43. Typical time histories of water-surface and hawser forces during a 6-min filling valve operation with valves 1, 2, and 4 operating and Type 15 Chamber Design.

valves 1, 2, and 3 operating. The filling times and average maximum hawser forces measured with valves 1, 2, and 4 operating are shown in Figure 44 and listed in Table 8. The 15-ton hawser force limit was reached on the upstream longitudinal hawser force with an 18-min filling time with a valve time slightly less than 6 min. The filling time versus valve time for this operation is shown in Figure 42.

3.10.4 Valves 2, 3, and 4 and 1, 3, and 4 operating

The tests with these valve operations were not considered necessary since they should be very similar to those conducted with 1, 2, and 3 and 1, 2, and 4 operating. The differences in these cases would be transverse hawser forces pushing the ship to the left side of the chamber. A 6-min valve operation should result in acceptable chamber performance with valves 2, 3, and 4 or valves 1, 3, and 4 operating with the 21.5-ft lift.

3.10.5 Valves 1 and 4 operating

Tests were conducted next with 2 valves operating. Operations with the outer valves, valves 1 and 4, will be discussed first. Typical time histories with these valves operating and a 4-min valve time are shown in Figure 45. The maximum longitudinal hawser force was 15.1 tons and occurred in the

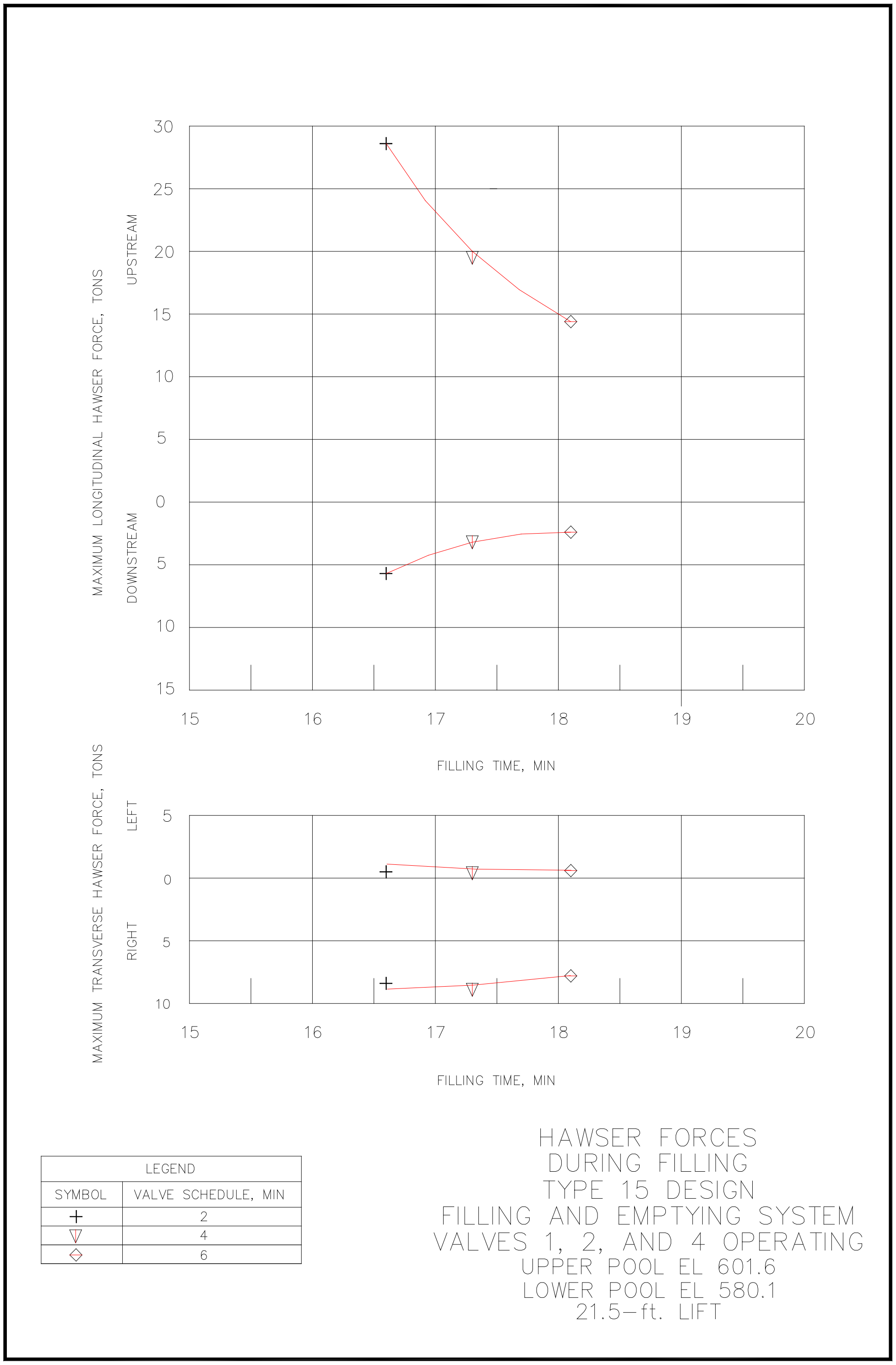


Figure 44. Average maximum hawser forces during filling with valves 1, 2, and 4 operating and Type 15 Chamber Design.

Table 8. Filling characteristics, Type 15 filling and emptying system, valves 1, 2, and 4 operating, 21.5-ft lift, upper pool el 601.6, lower pool el 580.1.

Valve Time (min)	Hawser Force (Tons)						Fill Time (min)
	Longitudinal		U/S Transverse		D/S Transverse		
	U/S	D/S	Right	Left	Right	Left	
2.0	28.8	-5.5	8.0		9.1	0	16.4
	28.4	-5.7	7.8	-0.5	7.6	-0.9	16.7
	30.5	-5.7	10.8	-0.4	9.6	-0.2	16.5
Average	29.2	-5.7	8.8	-0.3	8.7	-0.4	16.5
4.0							
	19.6	-3.1	7.9	-0	9.3	0	17.2
	19.3	-3.3	7.8	-0.8	8.4	-0.4	17.3
	20.7	-3.2	9.1	-0.3	7.9	-0.3	17.5
Average	19.9	-3.2	8.2	-0.4	8.5	-0.2	17.3
6.0							
	14.4	-2.3	6.5	-0.4	7.7	-0.3	18.0
	14.3	-2.4	8.1	-0.7	7.9	-0.4	18.1
	15.4	-2.4	9.5	-0.5	7.9	-0.2	18.2
Average	14.7	-2.4	8.0	-0.5	7.8	-0.3	18.1

upstream direction around 4 min into the filling operation. The transverse hawser forces were much less than the upstream longitudinal forces and indicated that the ship was pushed slightly to the right side of the chamber. This would indicate that culvert 1 is a little more efficient than culvert 4. The filling times and hawser forces measured with valves 1 and 4 operating are shown in Figure 46 and listed in Table 9. A filling time of 23.1 min was necessary to limit the maximum hawser force to 15 tons. Figure 42 provides a plot of filling time versus valve time for operations with valves 1 and 4 operating. A 4.0-min valve will provide an acceptable filling time for this case.

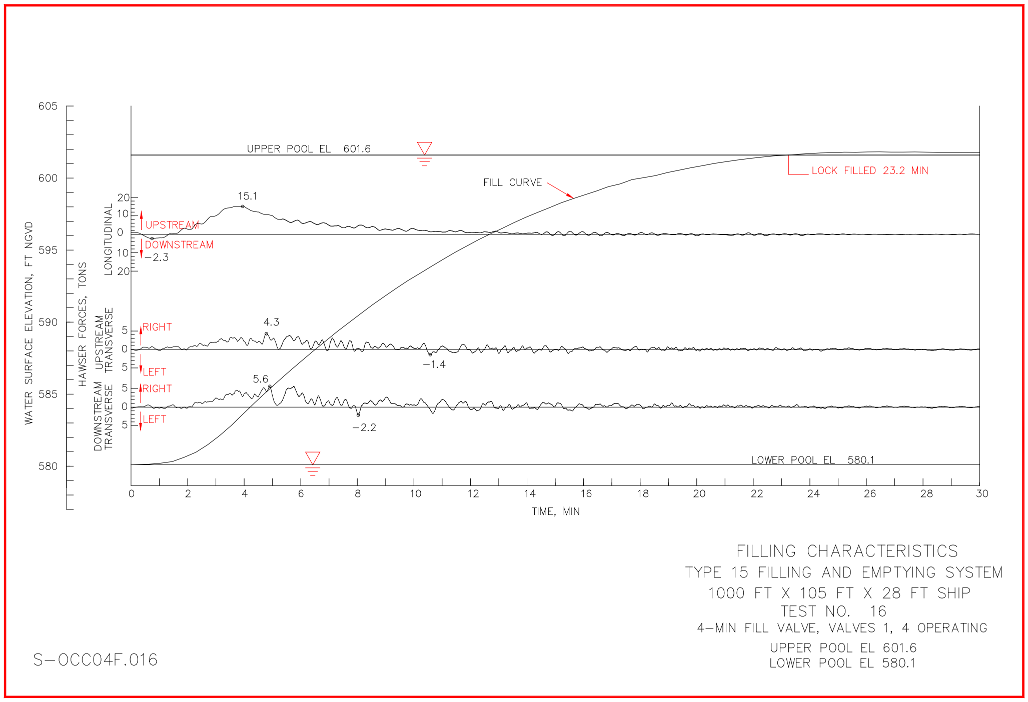


Figure 45. Typical time histories of water-surface and hawser forces during a 4-min filling valve operation with valves 1 and 4 operating and Type 15 Chamber Design.

3.10.6 Valves 2 and 3 operating

Typical time histories with these valves operating and a 4-min valve time are shown in Figure 47. The maximum longitudinal hawser force was 14.9 tons and occurred in the upstream direction around 4 min into the filling operation, very similar to valves 1 and 4 operating. The transverse hawser forces were all less than 2 tons and indicated that the ship stayed centered in the chamber during most of the filling operation. The filling times and hawser forces measured with valves 2 and 3 operating are shown in Figure 48 and listed in Table 10. A filling time of 23.2 min was necessary to limit the maximum hawser force to 15 tons. Figure 42 provides the filling times versus valve times for operations with valves 2 and 3 operating. A 4.2-min valve results in a 23.2 min filling time with valves 2 and 3 operating.

3.10.7 Valves 1 and 3 and 2 and 4 operating

Typical time histories with valves 1 and 3 operating with a 4-min valve time are shown in Figure 49. The maximum longitudinal hawser force was 14.1 tons and occurred in the upstream direction around 4 min into the filling operation, which is very similar to valves 1 and 4 operating. The transverse hawser forces were all less than 10 tons and indicated that the

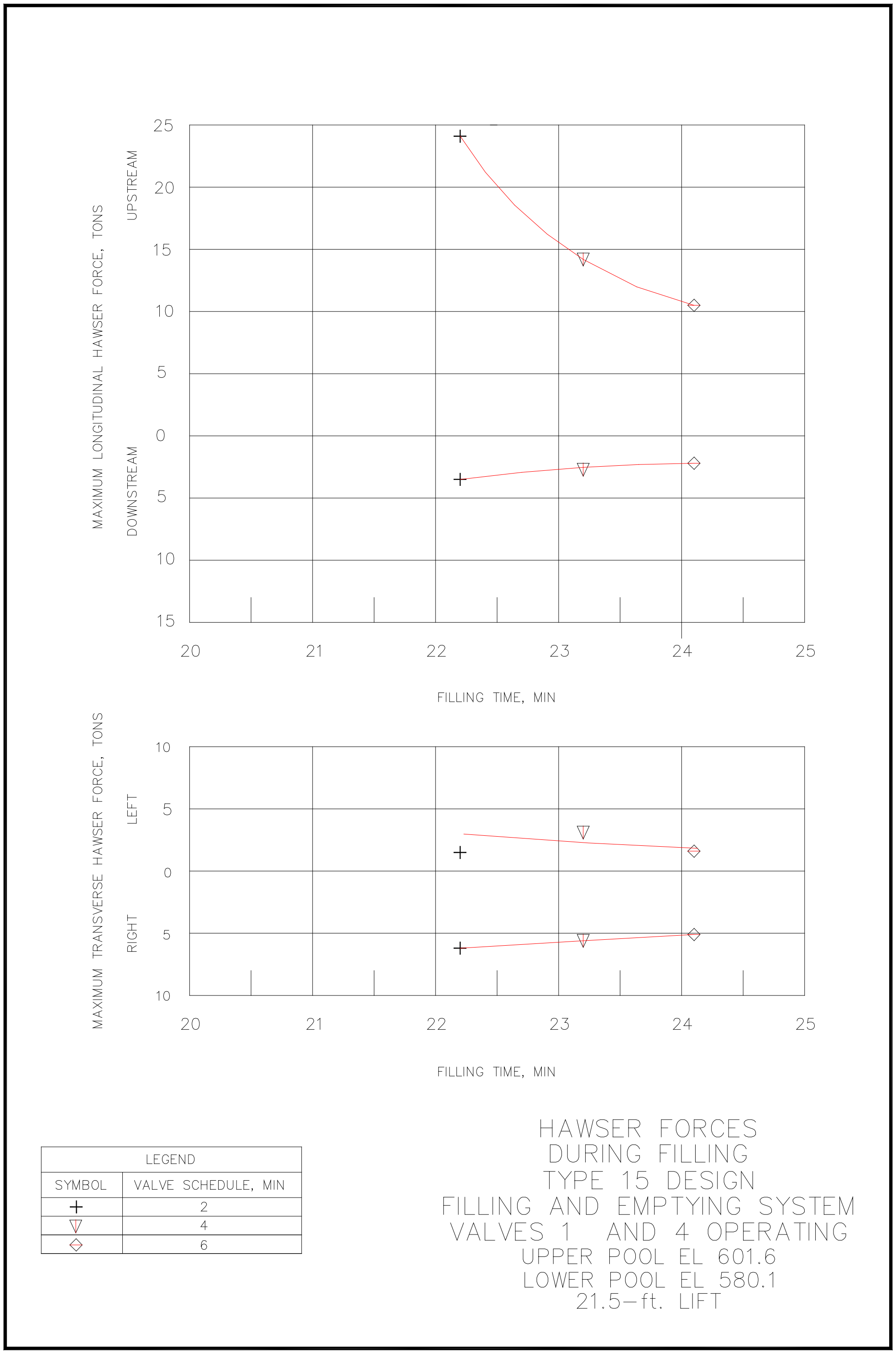


Figure 46. Average maximum hawser forces during filling with valves 1 and 4 operating and Type 15 Chamber Design.

Table 9. Filling characteristics, Type 15 Chamber Design, valves 1 and 4 operating, 21.5-ft lift, upper pool el 601.6, lower pool el 580.1.

Valve Time (min)	Hawser Forces (Tons)						Fill Time (min)
	Longitudinal		U/S Transverse		D/S Transverse		
	U/S	D/S	Right	Left	Right	Left	
2.0	25.2	-3.9	5.2	-1.4	5.7	-1.0	22.2
	23.3	-3.1	4.2	-1.8	6.5	-1.3	22.0
	23.7	-3.6	5.8	-1.4	6.5	-1.2	22.3
Average	24.1	-3.5	5.1	-1.5	6.2	-1.2	22.2
4.0							
	15.1	-2.3	4.3	-1.4	5.6	-2.2	23.2
	13.9	-2.3	4.3	-1.5	5.4	-1.5	23.3
	14.7	-2.0	4.8	-3.1	5.6	-1.2	23.1
Average	14.6	-2.2	4.5	-2.0	5.6	-1.6	23.2
6.0							
	11.7	-2.4	3.9	-1.3	4.3	-1.0	24.2
	10.9	-1.9	3.4	-1.2	5.1	-2.2	23.9
Average	10.5	-2.2	3.7	-1.3	4.7	-1.6	24.1

ship was pushed slightly to the right side of the chamber during most of the filling operation. This observation indicates that culvert 1 was slightly more efficient than culvert 3. The filling times and hawser forces measured with valves 1 and 3 operating are shown in Figure 50 and listed in Table 11. A filling time of 22.9 min was necessary to limit the maximum hawser force to 15 tons. Figure 42 provides a plot of filling time versus valve time for operations with valves 1 and 3 operating. A 4-min valve will provide acceptable chamber performance with valves 1 and 3 operating. A 4-min valve time will also provide acceptable chamber performance with valves 2 and 4 operating.

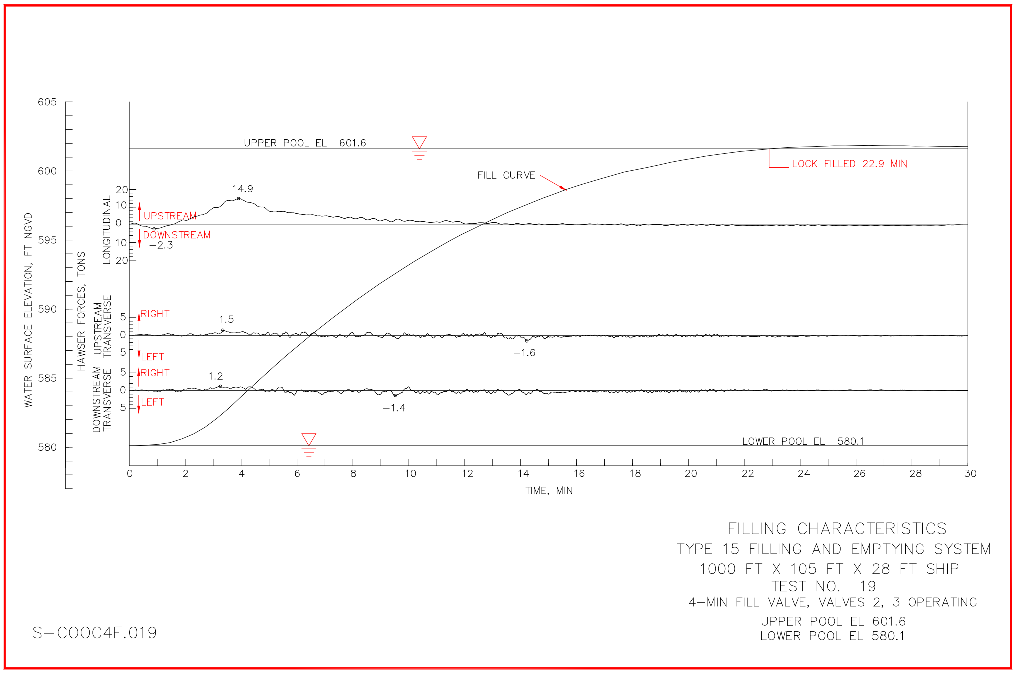


Figure 47. Typical time histories of water-surface and hawser forces during a 4-min filling valve operation with valves 2 and 3 operating and Type 15 Chamber Design.

3.10.8 Valves 1 and 2 operating

Typical time histories with valves 1 and 2 operating and a 2-min valve time are shown in Figure 51. The maximum longitudinal hawser force was 20.4 tons and occurred in the upstream direction just after 2 min into the filling operation. The maximum transverse hawser force occurred on the downstream right side and was 14.5 tons. The transverse forces indicated that the ship was pushed to right side of the chamber during the filling operation. This should be expected since culverts 1 and 2 were discharging on the left side of the chamber causing the water-surface to be higher on this side. The filling times and average maximum hawser forces measured with valves 1 and 2 operating are shown in Figure 52 and listed in Table 12. A filling time of 26.8 min was necessary to limit the maximum hawser force to 15 tons. Figure 53 provides the filling times versus valve times for operations with valves 1 and 2 operating. A 4.5-min valve will provide acceptable longitudinal hawser forces with valves 1 and 2 operating. The right side transverse forces were close to 15 tons for all valve operations tested, indicating that care should be taken if this situation arises. The unequal distribution of flow into the chamber caused the high transverse forces.

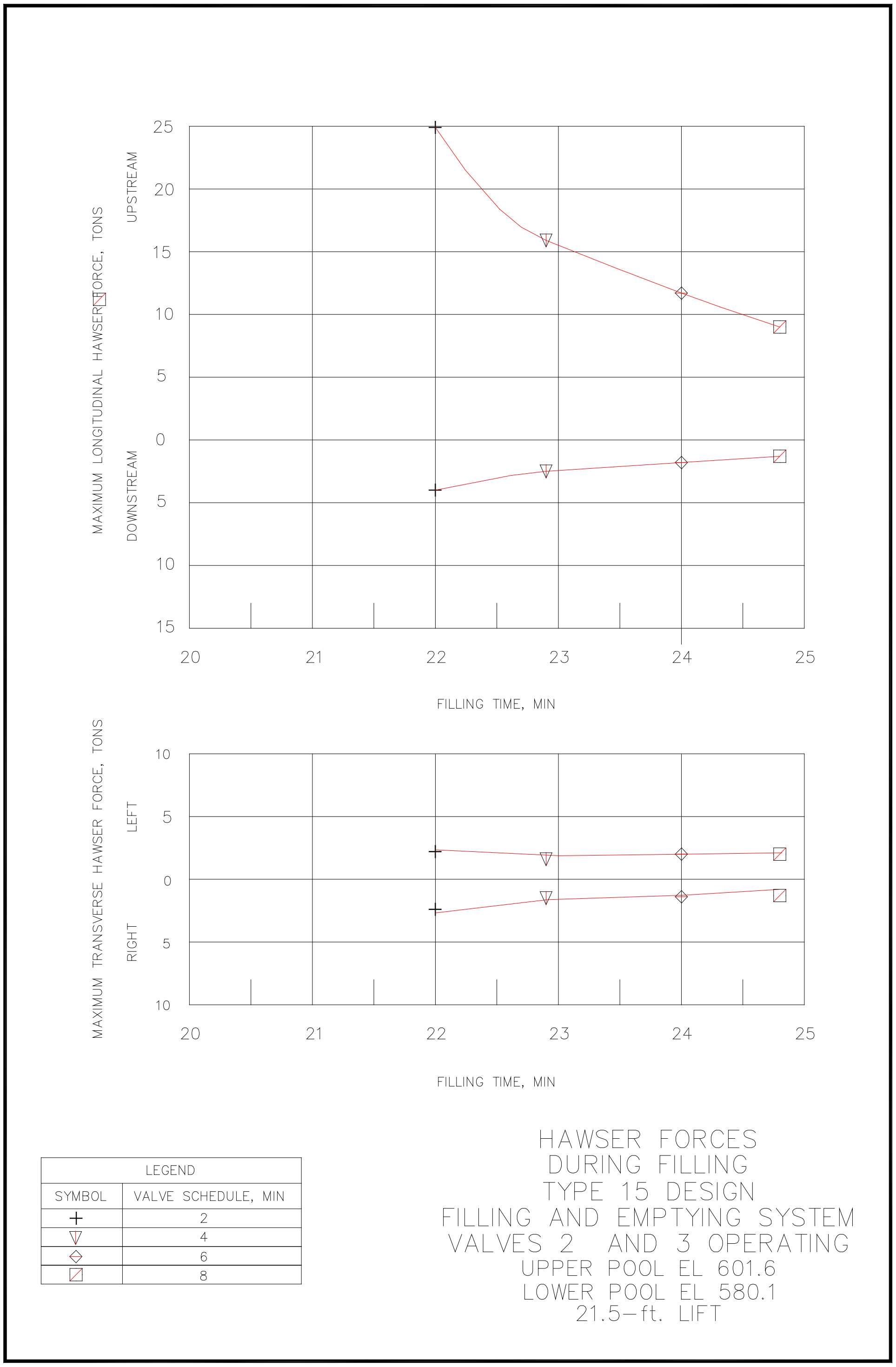


Figure 48. Average maximum hawser forces during filling with valves 2 and 3 operating and Type 15 Chamber Design.

Table 10. Filling characteristics, Type 15 Chamber Design, valves 2 and 3 operating, 21.5-ft lift, upper pool el 601.6, lower pool el 580.1.

Valve Time (min)	Hawser Forces (Tons)						Fill Time (min)
	Longitudinal		U/S Transverse		D/S Transverse		
	U/S	D/S	Right	Left	Right	Left	
2.0	25.9	-4.2	2.0	-1.9	2.0	-1.7	22.0
	23.9	-3.7	2.8	-0.8	2.6	-2.6	22.0
	24.9	-4.1	2.8	-1.6	2.4	-1.7	22.2
Average	24.9	-4.0	2.5	-1.4	2.3	-2.0	22.1
4.0							
	16.9	-2.7	1.8	-1.8	1.7	-1.6	22.8
	14.9	-2.3	1.5	-1.6	1.2	-1.4	22.9
	15.4	-2.2	1.5	-2.0	1.6	-1.5	22.9
Average	15.7	-2.4	1.6	-1.8	1.5	-1.5	22.9
6.0							
	12.5	-1.8	1.1	-1.6	1.1	-2.0	24.0
	10.9	-1.7	1.6	-1.4	1.7	-1.9	24.0
	12.1	-1.4	1.4	0	1.8	-2.1	24
Average	11.8	-1.6	1.4	-1.0	1.5	-2.0	24.0
8.0							
	9.1	-1.5	1.1	-1.6	1.6	-2.4	24.8
	8.9	-1.1	1.4	-1.7	1.1	-1.5	24.8
	9.2	-1	0.9	-2.1	1.0	-2.1	25.1
Average	9.1	-1.2	1.1	-1.8	1.2	-2.0	24.9

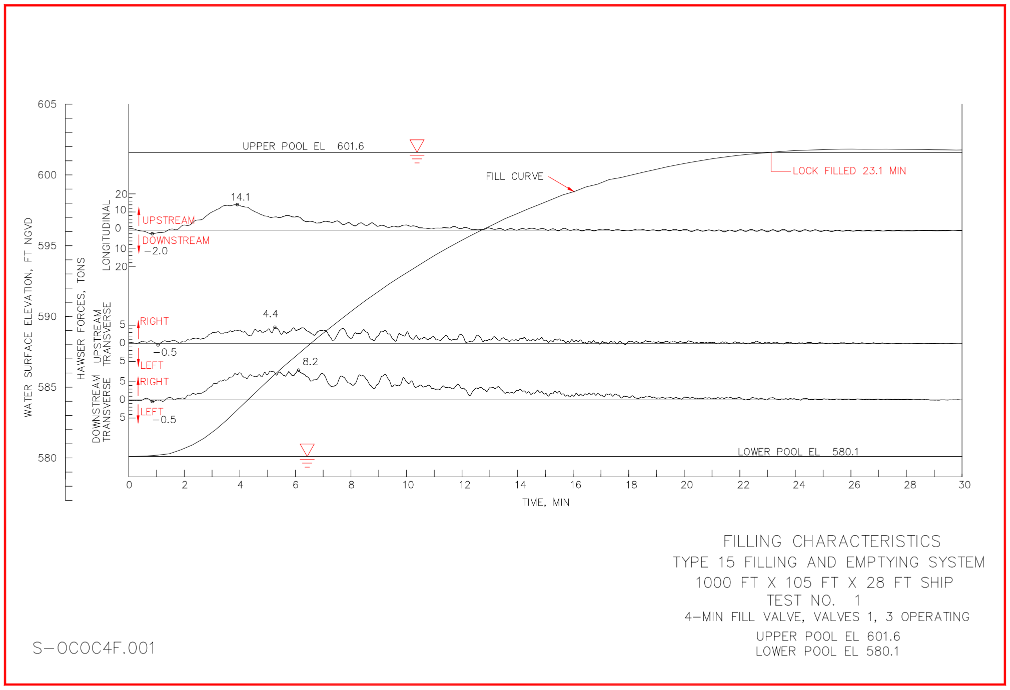


Figure 49. Typical time histories of water-surface and hawser forces during a 4-min filling valve operation with valves 1 and 3 operating and Type 15 Chamber Design.

3.10.9 Valves 3 and 4 operating

Typical time histories with valves 3 and 4 operating and a 4-min valve time are shown in Figure 54. The maximum longitudinal hawser force was 11.6 tons and occurred in the upstream direction just after 3 min into the filling operation. The maximum transverse hawser forces occurred on the left side and were less than 10 tons. The transverse forces indicated that the ship was pushed to left side of the chamber during the filling operation and was expected, since culverts 3 and 4 were discharging on the right side of the chamber causing the water-surface to be higher on this side. The filling times and hawser forces measured with valves 3 and 4 operating are shown in Figure 55 and listed in Table 13. A filling time of 28.8 min was necessary to limit the maximum hawser force to 15 tons. Figure 53 provides the filling times versus valve times for operations with valves 3 and 4 operating. A valve time slightly less than 3 min will provide acceptable longitudinal hawser forces with valves 3 and 4 operating.

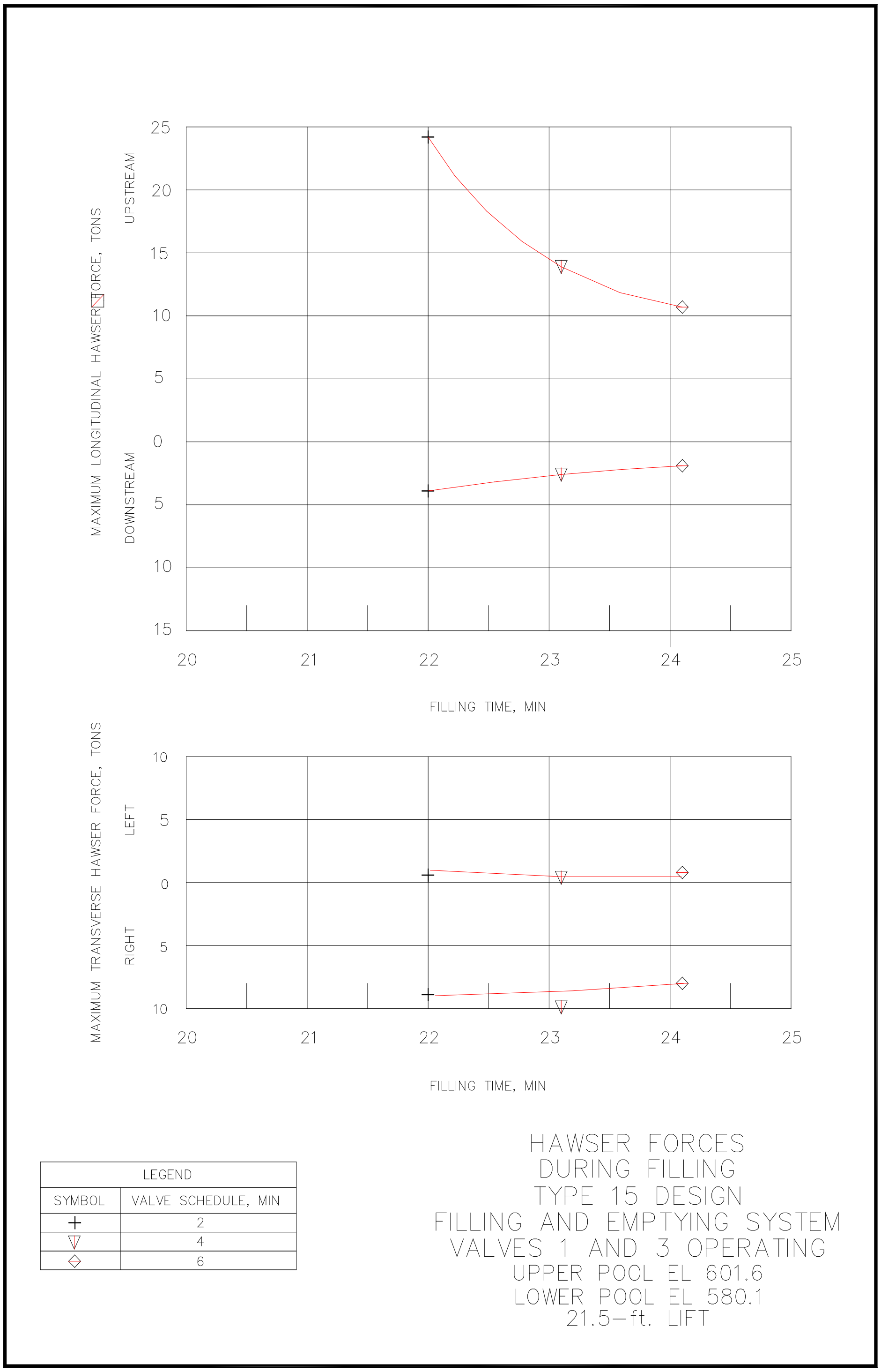


Figure 50. Average maximum hawser forces during filling with valves 1 and 3 operating and Type 15 Chamber Design.

Table 11. Filling characteristics, Type 15 Chamber Design, valves 1 and 3 operating, 21.5-ft lift, upper pool el 601.6, lower pool el 580.1.

Valve Time (min)	Hawser Forces (Tons)						Fill Time (min)
	Longitudinal		U/S Transverse		D/S Transverse		
	U/S	D/S	Right	Left	Right	Left	
2.0	24.5	-3.9	5.4	-0.7	8.6	-0.4	21.7
	23.8	-3.9	5.1	-0.4	9.2	-0.3	22.2
	24.6	-3.4	6.6	-0.4	9.4	-0.2	22.8
Average	24.3	-3.7	5.7	-0.5	9.1	-0.3	22.2
4.0							
	14.1	-2.9	4.4	-0.5	8.2	-0.5	23.1
	13.7	-2.3	5.2	-0.3	11.4	-0.3	23.0
	14.6	-2.1	5.4	-0.4	9.2	-0.3	23
Average	14.1	-2.4	5.0	-0.4	9.6	-0.4	23.0
6.0							
	10.8	-1.7	4.3	-0.9	7.5	-0.3	24.1
	10.5	-2.1	4.5	-0.7	8.5	-0.4	24.1
	10.6	-1.5	6.2	-0.3	9.2	-0.3	24
Average	10.6	-1.8	5.0	-0.6	8.4	-0.4	24.1

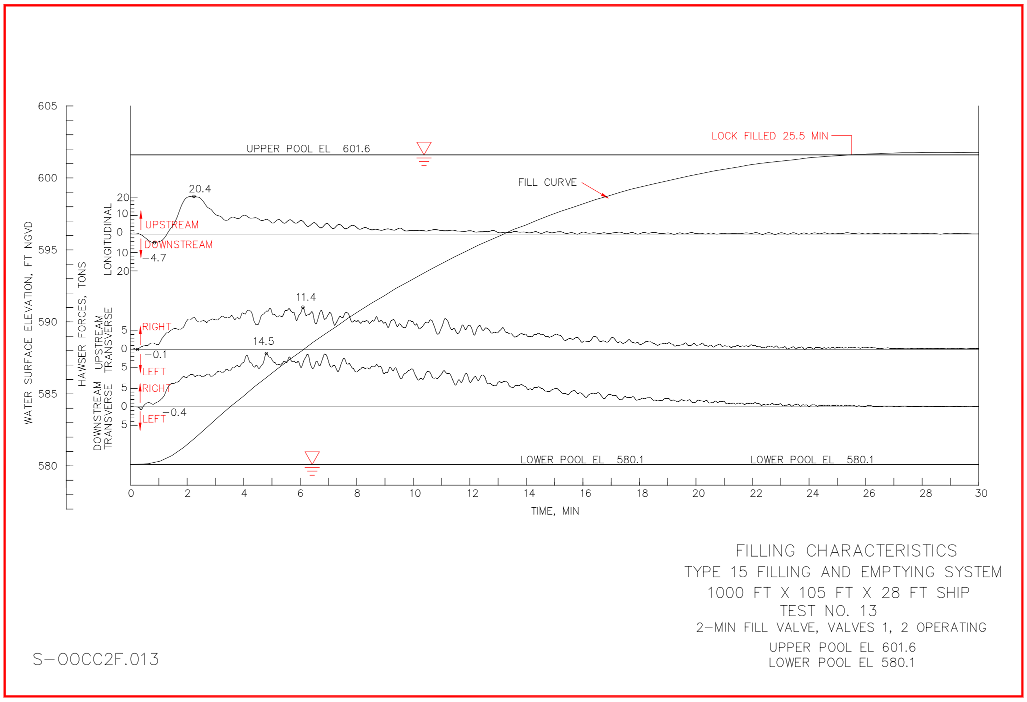


Figure 51. Typical time histories of water-surface and hawser forces during a 2-min filling valve operation with valves 1 and 2 operating and Type 15 Chamber Design.

3.10.10 Valve 1 operating

Tests were performed next with only valve 1 operating. Typical time histories with valve 1 operating and a 2-min valve time are shown in Figure 56. The maximum longitudinal hawser force was 14.6 tons and occurred in the upstream direction around 2 min into the filling operation. The maximum transverse hawser forces occurred on the right side and were equal to or less than 6 tons. The transverse forces indicated that the ship was pushed to right side of the chamber during the filling operation, which was expected since culvert 1 discharges on the left side of the chamber, causing the water-surface to be higher. The filling times and average maximum hawser forces measured with valve 1 operating are shown in Figure 57 and listed in Table 14. A filling time of 42 min was necessary to limit the maximum hawser force to 15 tons. A 2-min valve time will provide acceptable performance with valve 1 operating and a 21.5-ft lift.

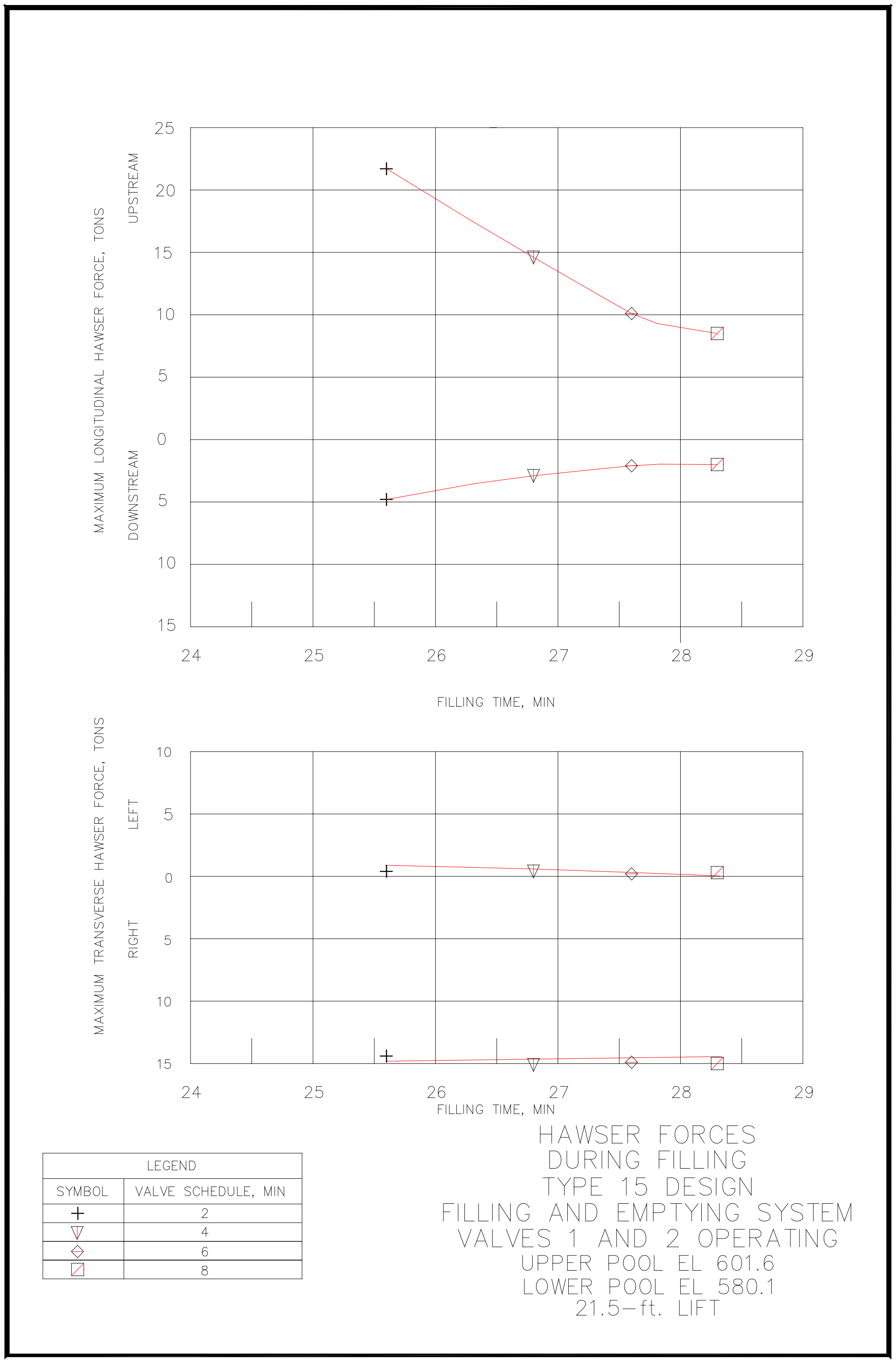


Figure 52. Average maximum hawser forces during filling with valves 1 and 2 operating and Type 15 Chamber Design.

Table 12. Filling characteristics, Type 15 filling and emptying system, valves 1 and 2 operating, 21.5-ft lift, upper pool el 601.6, lower pool el 580.1.

Valve Time (min)	Hawser Forces (Tons)						Fill Time (min)
	Longitudinal		U/S Transverse		D/S Transverse		
	U/S	D/S	Right	Left	Right	Left	
2.0	22.5	-4.9	10.4	-0	21.2	-0.4	25.6
	20.4	-4.7	11.4	-0.1	14.5	-0.4	25.5
	22.2	-4.8	10.2	-0.4	14.3	-0.3	25.8
Average	21.7	-4.8	10.7	-0.2	14.4	-0.4	25.6
4.0							
	15.2	-2.9	8.1	-0.4	15.1	-0.4	26.5
	14.5	-3.4	8.2	-0.4	15.0	-0.3	26.9
	14.2	-2.9	10.4	-0.4	14.9	-0.5	26.9
Average	14.6	-3.1	8.9	-0.4	15.0	-0.4	26.8
6.0							
	10.0	-2.1	11.8	-0.3	14.4	-0.3	27.4
	10.1	-2.1	10.0	-0	15.3	-0	27.7
Average	10.1	-2.1	10.9	-0.2	14.9	-0.2	27.6
8.0							
	8.3	-1.9	12.0	-0.2	15.4	-0	28.3
	8.1	-1.8	11.1	-0.3	15.4	-0.2	28.1
	9.0	-2.3	10.7	-0.4	14.4	-0.5	28.6
Average	8.5	-2.0	11.3	-0.3	15.0	-0.2	28.3

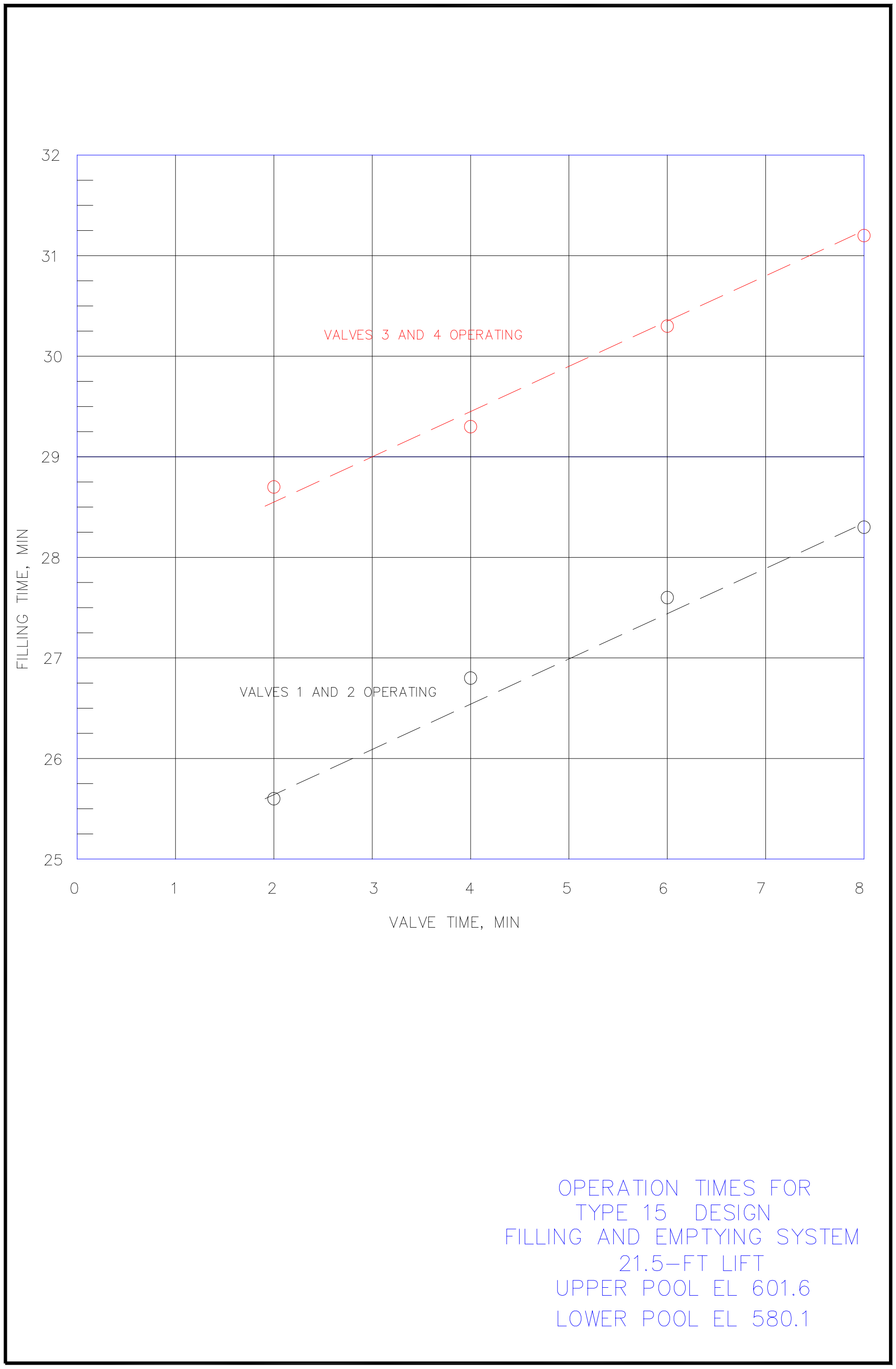


Figure 53. Filling time versus valve time for 2 valves operating and Type 15 Chamber Design.

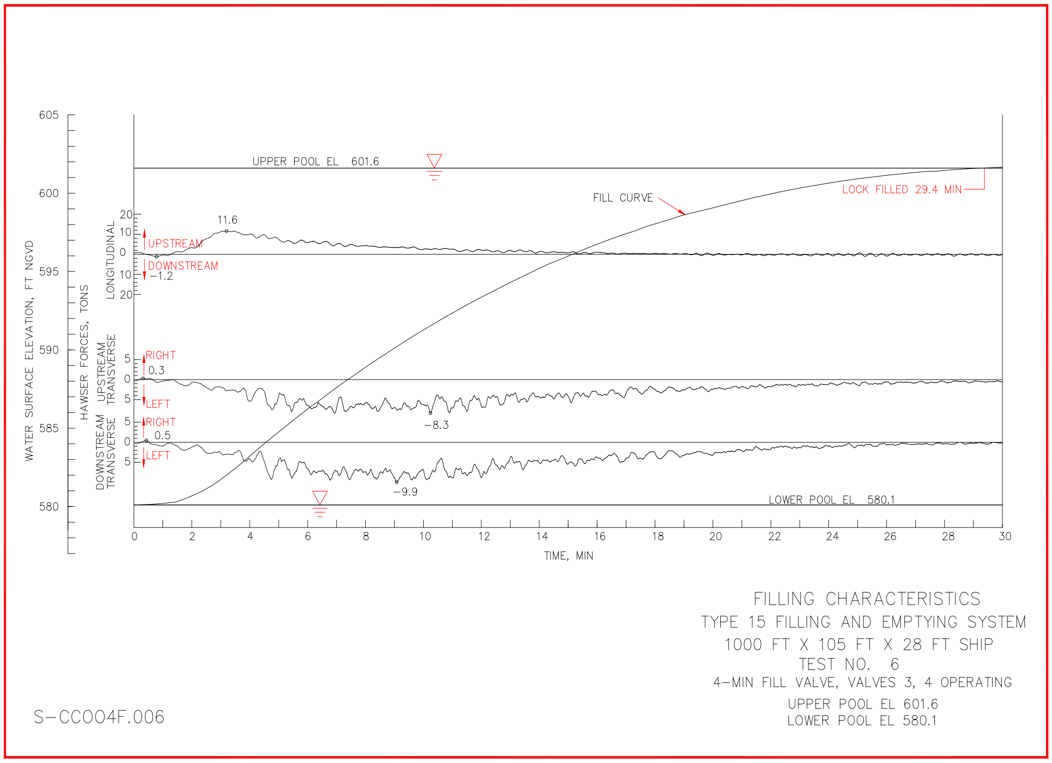


Figure 54. Typical time histories of water-surface and hawser forces during a 4-min filling valve operation with valves 3 and 4 operating and Type 15 Chamber Design.

3.10.11 Valve 2 operating

Tests were performed next with valve 2 operating. Typical time histories with valve 2 operating and a 2-min valve time are shown in Figure 58. The maximum longitudinal hawser force was 17.3 tons and occurred in the upstream direction around 2 min into the filling operation. The maximum transverse hawser forces occurred on the right side and were less than 4 tons. The transverse forces indicated that the ship was pushed to right side of the chamber during the filling operation, which was expected since culvert 2 discharges on the left side of the chamber causing the water-surface to be higher on this side. The filling times and average maximum hawser forces measured with valve 2 operating are shown in Figure 59 and listed in Table 15. Similarly to valve 1 operating, a filling time of 42 min was necessary to limit the maximum hawser force to 15 tons. A 2.5-min valve time provided a filling time of 42.0 min with valve 2 operating.

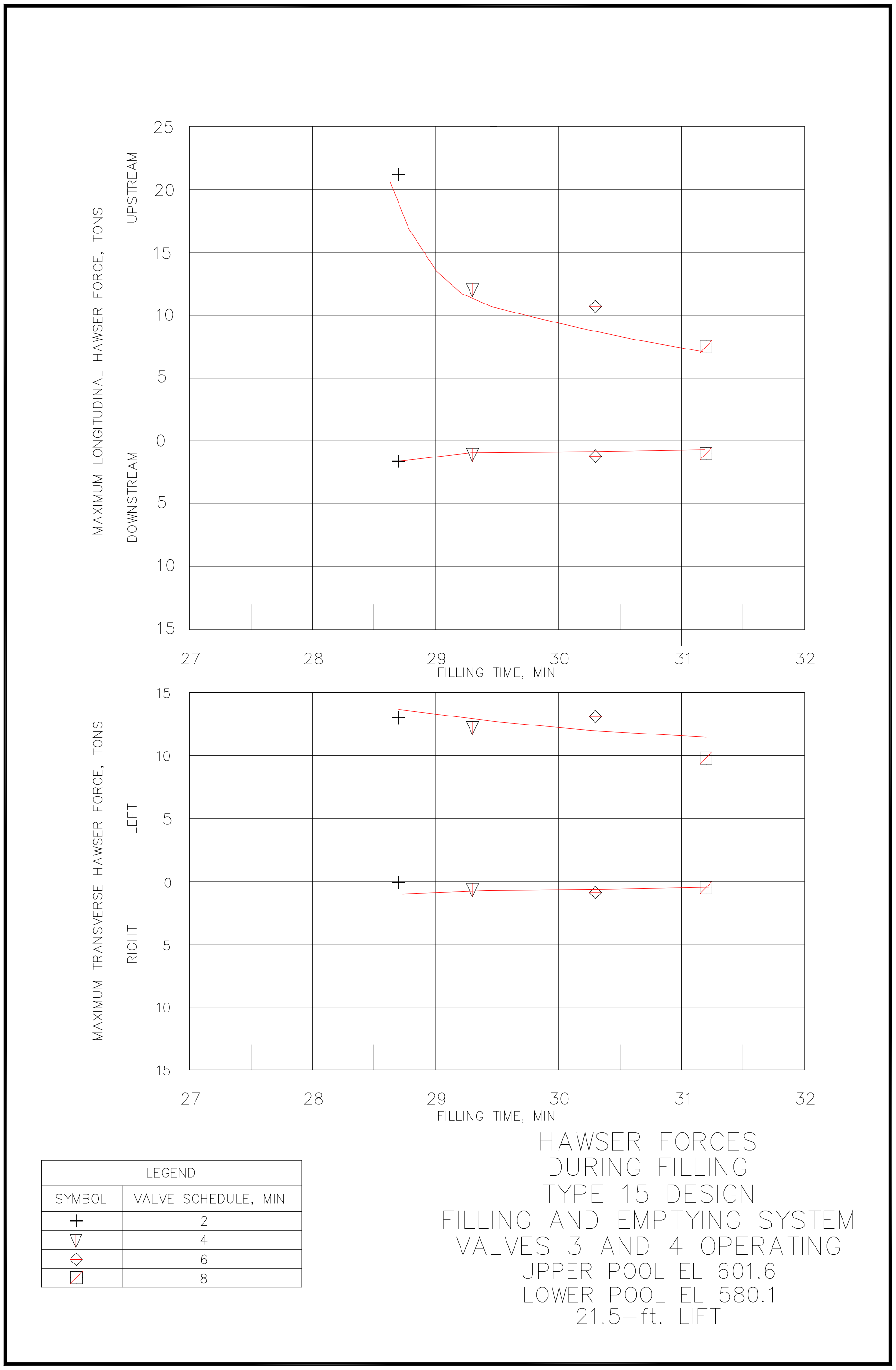


Figure 55. Average maximum hawser forces during filling with valves 3 and 4 operating and Type 15 Chamber Design.

Table 13. Filling characteristics, Type 15 Chamber Design, valves 3and 4 operating, 21.5-ft lift, upper pool el 601.6, lower pool el 580.1.

Valve Time (min)	Hawser Forces (Tons)						Fill Time (min)
	Longitudinal		U/S Transverse		D/S Transverse		
	U/S	D/S	Right	Left	Right	Left	
2.0	21.2	-1.7	0	-8.1	0	-16.0	28.5
	20.5	-1.7	0	-10.3	0	-12.5	
	20.5	-1.4	0.4	-8.8	0.4	-10.5	28.9
Average	20.7	-1.6	0.1	-9.1	0.1	-13.0	28.7
4.0							
	12.5	-1.1	0.3	-8.6	1.0	-16.2	29.3
	11.8	-1.1	0.4	-9.8	0.5	-10.6	29.2
	11.6	-1.2	0.3	-8.3	0.5	-9.9	29.4
Average	12.0	-1.1	0.3	8.9	0.7	-12.2	29.3
6.0							
	11.0	-1.2	0.5	-8.7	1.3	-17.8	30.5
	9.1	-1.2	0.5	-8.6	0.6	-10.8	30.2
	8.8	-1.2	0.6	-8.7	0.8	-10.7	30.1
Average	10.7	-1.2	0.5	-8.7	0.9	-13.1	30.3
8.0							
	7.5	-0.8	0.3	-9.3	0.4	-10.2	31.5
	7.3	-1.1	0.3	-7.6	0.6	-9.9	31.1
	7.8	-1.2	0.6	-8.0	0.6	-9.4	31.0
Average	7.5	-1.0	0.4	-8.3	0.5	-9.8	31.2

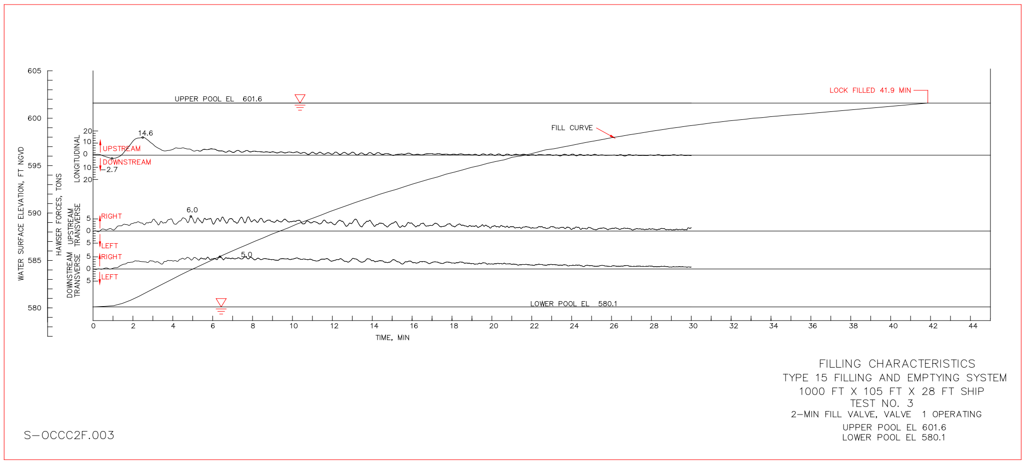


Figure 56. Typical time histories of water-surface and hawser forces during a 2-min filling valve operation with valve 1 operating and Type 15 Chamber Design.

3.10.12 Valve 3 and valve 4 operating

Tests were not conducted with these operations due to time limitations. Chamber performance with valve 4 operating should be similar to valve 1 operations and valve 3 operations should be similar to valve 2 operations. Lock filling times with valve 4 only or valve 3 only will be slightly slower than with valves 1 or 2. This observation was based on the filling times shown in Figure 53.

3.10.13 Summary of non-standard valve operations for lock filling

Table 16 provides a summary of the permissible filling times and associated valve times to achieve these filling times for non standard valve operations. The model test results indicate generally that with 3 valves operating, a 6-min valve time should be used; with 2 valves operating, a 4-min valve time should be used; and with 1 valve operating, a 2- to 3-min valve time should be used.

3.10.14 Non-standard lock emptying operations

The chamber performance during lock emptying showed that a 1-min valve could be used for all valve combinations. The turbulence in the chamber was minimal during lock emptying. Typical time histories obtained with a 1-min valve and valves 1, 2, and 3 operating are shown in Figure 60. The maximum hawser force was 3.8 tons and was measured on the downstream longitudinal hawser near 1 min into the filling operation. The transverse hawser forces were insignificant. The lock emptied in 18.4 min with these valves operating.

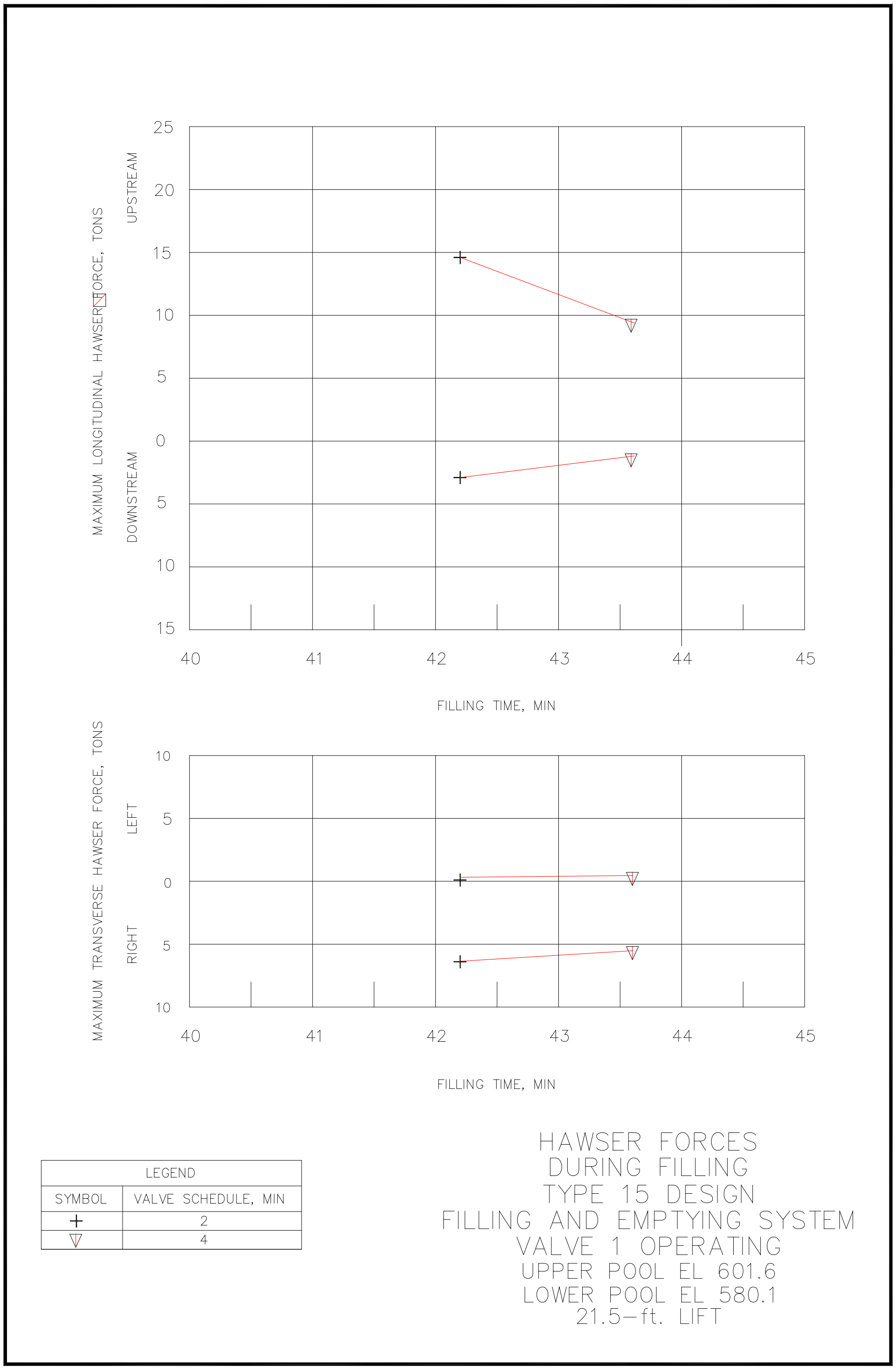


Figure 57. Average maximum hawser forces during filling with valve 1 operating and Type 15 Chamber Design.

Table 14. Filling characteristics, Type 15 Chamber Design, valve 1 operating, 21.5-ft lift, upper pool el 601.6, lower pool el 580.1.

Valve Time (min)	Hawser Forces (Tons)						Fill Time (min)
	Longitudinal		U/S Transverse		D/S Transverse		
	U/S	D/S	Right	Left	Right	Left	
2.0	14.6	-3.3	7.2	-0.2	5.1	-0.1	43.6
	14.4	2.7	6.1	-0	5.2	-0.2	41.2
	14.6	-2.7	6.0	0	5.0	0	41.9
Average	14.6	-2.9	6.4	-01	5.1	-0.1	42.2
4.0							
	9.4	-1.0	5.6	-0	5.4	-0.3	43.6
	9.1	-1.9	5.7	-0	5.2	-0.1	43.6
	8.8	-1.8	5.9	-0.5	5.2	-0.1	43.6
Average	9.1	-1.6	5.7	-0.2	5.2	-02	43.6

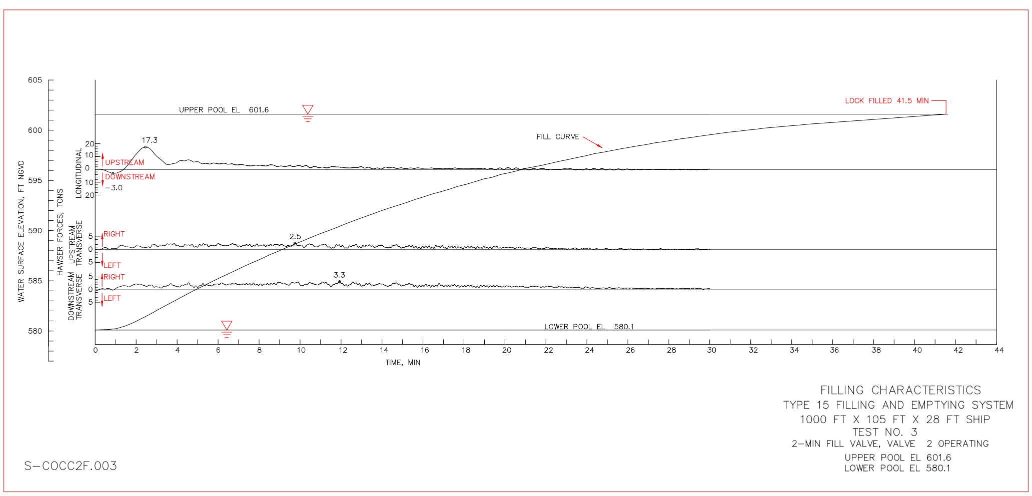


Figure 58. Typical time histories of water-surface and hawser forces during a 2-min filling valve operation with valve 2 operating and Type 15 Chamber Design.

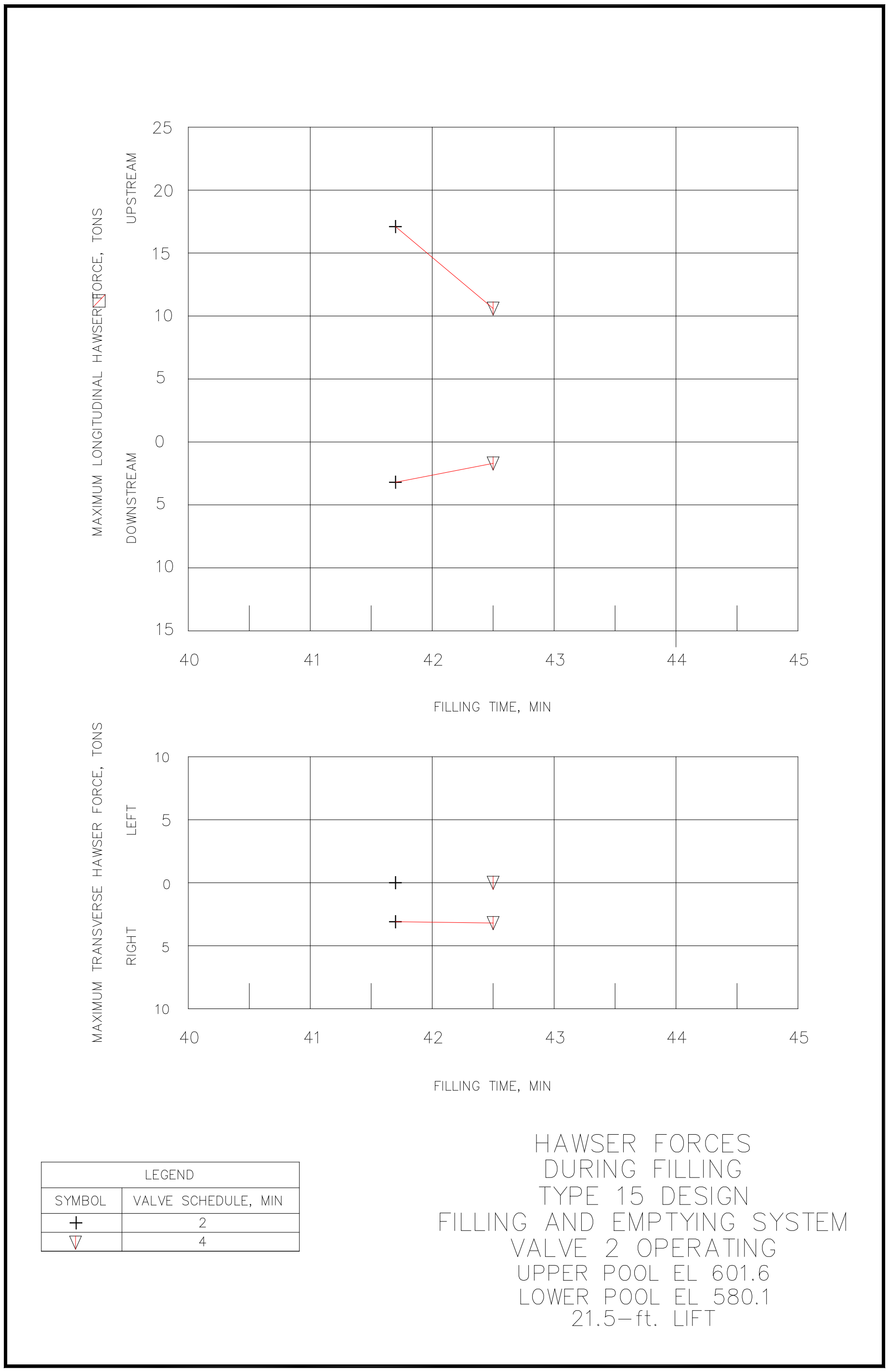


Figure 59. Average maximum hawser forces during filling with valve 2 operating and Type 15 Chamber Design.

Table 15. Filling characteristics, Type 15 Chamber Design, valve 2 operating, 21.5-ft lift, upper pool el 601.6, lower pool el 580.1.

Valve Time (min)	Hawser Forces (Tons)						Fill Time (min)
	Longitudinal		U/S Transverse		D/S Transverse		
	U/S	D/S	Right	Left	Right	Left	
2.0	16.6	-3.2	2.6	-0	3.1	-0	41.9
	17.5	-3.2	3.0	-0	2.9	-0	41.6
	17.3	-3.0	2.5	0	3.3	0	41.5
Average	17.1	-3.2	2.7	-0	3.1	-0	41.7
4.0							
	11.6	-1.9	2.6	-0	3.4	-0	41.8
	10.5	-1.4	2.2	-0	3.0	-0	42.4
	9.8	-1.8	2.2	-0	3.3	-0	43.4
Average	10.6	-1.7	2.3	-0	3.2	-0	42.5

Table 16. Permissible filling times, and associated valve times, Type 15 Chamber Design, 21.5-ft lift, upper pool el 601.6, lower pool el 580.1.

Valves Operating	Permissible Filling Time, min	Associated Valve Time, min
1, 2, 3, and 4	16.1	8.0
1, 2, and 3	18.3	6.1
1, 2, and 4	18.0	6.0
2, 3, and 4	18.0	6.0
1, 3, and 4	18.0	6.0
1 and 4	23.1	4.0
2 and 3	23.2	4.2
1 and 3	22.9	4.0
2 and 4	23.0	4.0
1 and 2	26.8	4.5
3 and 4	28.8	3.0
1	42.0	2.0
2	42.0	2.5
3*	42.0	2.5
4*	42.0	2.0

*Filling times and valve operations based on results from valves 1 and 2

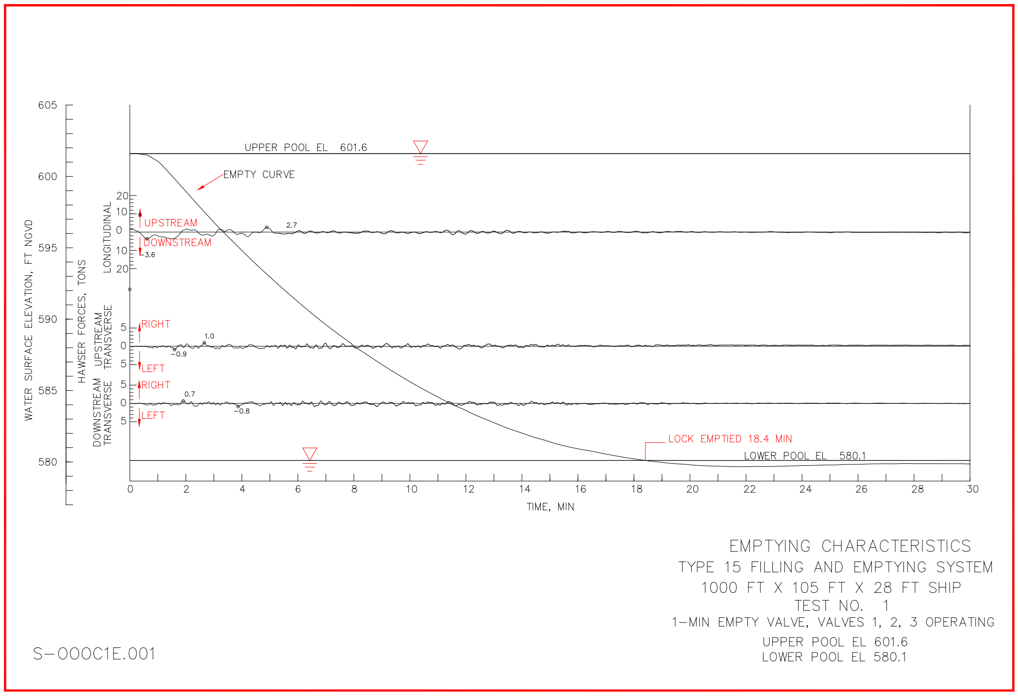


Figure 60. Typical time histories of water-surface and hawser forces during a 1-min emptying valve operation with valves 1, 2, and 3 operating and Type Chamber Design.

4 Summary and Conclusions

Results from the intake vortex experiments with the Types 8 and 9 Intake Designs indicated that the entrance should be mounted flush with an upstream face wall. If the individual valve housings are mounted so that they project upstream from the face of the upper miter sill, then increased vortex activity should be expected. The emergency gate sill located 125 ft upstream from the upper miter sill did not affect the approach flow adversely during lock filling. Changing the orientation of the filling and emptying valves from rotating about a horizontal axis to rotating about a vertical axis, showed a slight increase in vortex activity with the vertical axis. The vortex activity was similar with the valves opening either clockwise or counter-clockwise.

The permissible filling time with the Type 13 Chamber Design was considerably slower than the Type 12 Chamber Design. During emptying the two designs performed similarly. The Type 13 Chamber Design tried to incorporate the features of the Type 12 Chamber Design within the 3-ft thickness of the lock floor. The headlosses in the lower ports of the Type 13 Chamber Design were greater than the upper ports, which caused excessive downstream hawser forces during lock filling.

The results from the lock chamber experiments showed that the Type 14 Chamber Design was also considerably slower than the Type 12 Chamber Design during filling and only slightly faster than the Type 13 Chamber Design. Large downstream hawser forces were observed during lock filling indicating that more flow discharged in the upper end of the chamber. More flow discharged through the upper ports and less flow through the lower ports due to the headlosses in the culvert. During emptying, the chamber performance observed with the Type 14 Chamber Design was slower than that observed with the Type 12 Chamber Design. This is also an indication that this design has more headlosses than the previous designs evaluated. The Type 14 Chamber Design did not improve the lock performance.

The design philosophy was changed from the previous systems from that of an end filling longitudinal culvert system to a center distributed longitudinal system. Most center distributed longitudinal culvert systems have culverts located outside the chamber that run along the lock wall and supply water to the center of the chamber where it is split and fed in both the upstream and downstream directions. The downstream momentum of the flow in the culverts is redirected perpendicular to the chamber once the culvert turns and enters the center distribution system. This provides essentially a uniform distribution of flow to the ported culverts located in the upstream and downstream portions of the chamber. The Type 15 Chamber Design had the supply culverts inside the chamber underneath the lock floor and adjacent to the ported culverts. There was not enough width of chamber to turn the culverts so that they entered the center distribution system perpendicular to the chamber. The flow to the upstream ported culverts had to make a 180 degree turn from the supply culverts before feeding the upstream ported culverts and the f low supplied to the downstream ported culverts did not have to make a turn.

The permissible filling time determined for the Type 15 Chamber Design was 16.1 min and was achieved with a 7.4 min filling valve. The emptying time with a 1-min valve operation was 16.5 min and the hawser forces were less than 15 tons. A 1-min valve was considered to be very fast so no tests were performed with faster valve speeds. The hawser force measurements indicated that an upstream longitudinal hawser force occurred throughout most of the filling operation. This is caused by more flow discharging through the lower ports. The steady state pressure measurements also showed that the piezometric pressures were less in the upper ports than the lower ports.

Attempts were made to redistribute the flow by adding ports to the upper end of the chamber and blocking ports off in the lower end. The Type 16 Chamber Design contained 48 ports (57%) in the upper half of the chamber and 36 ports (43%) in the lower half of the chamber. The eight additional ports in the upper end of the chamber were placed in the supply culverts. The permissible filling time determined for the Type 16 Chamber Design filling and emptying system was 16.3 min and can be achieved with a 10.4 min filling valve. The emptying time with a 1-min valve operation was 14.4 min. Again, no faster valve operations were evaluated.

The Type 17 Chamber Design contained 48 upper ports (60%) and the lower chamber contained 32 ports (40%). The permissible filling time determined for the Type 17 Chamber Design was 15.9 min and can be achieved with a 7.9 min filling valve. The emptying time with a 1-min valve operation was

14.5 min. There was only a slight improvement in permissible filling time between the Type 15 and Type 17. One advantage of the Type 17 Chamber Design is that the emptying time with a 1-min valve is 2 min faster than the Type 15 Chamber Design. A disadvantage with the Type 17 Chamber Design is the excessive surface turbulence in the upper end of the lock when there is no ship in the chamber. This might be a safety issue for small craft. Another concern with the Type 17 Chamber Design is the increased chance for pressure transients in the culverts during filling operations due to the ports in the supply culverts. These transients should not be harmful to the culverts, but they could cause temporary surges in the port flow. The Type 15 Chamber Design is recommended based on the results to date. Table 17 summarizes the permissible filling times determined for the Types 13-17 Chamber Designs.

Table 17. Comparison of permissible filling times, Types 13-17 Chamber Designs, upper pool el 601.6, lower pool el 580.1.

Design	Permissible Filling Time, min
13	24.6
14	23.0
15	16.1
16	16.3
17	15.9

A 15-ft roof extension is recommended to reduce vortex strength to an acceptable level if the axis of the valve is mounted vertically. Vortices should be expected to form during lock filling. If the roof extension is installed, these vortices will be weak and should not cause any safety, ice or debris problems.

A modification to the Type 15 Chamber Design that might improve performance would be ports that connect the supply culverts to the ported culverts in the area between the intake and the first row of ports. This should increase pressure in the ported culverts and allow more discharge from the upstream ports.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

The U.S. Army Corps of Engineers, Detroit District, requested that the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL) evaluate the hydraulic performance of the new lock proposed for construction at the Soo Locks project in Sault Ste. Marie, Michigan. The lock will replace the existing Davis and Sabin locks in the North Canal. Currently, the Poe Lock is the only facility at Soo Locks capable of handling the Great Lakes system's largest vessels which account for more than half of the potential carrying capacity of the Great Lakes fleet. A laboratory model study was performed to evaluate the lock filling and emptying system and ice lockage procedures. Model investigations between 2003 and 2005 were reported in Hite and Tuthill 2005.

This report provides results of additional model experiments performed during the period 2005 – 2010 for the new lock. Modifications including new intake and filling and emptying system designs were evaluated. Additional intake experiments were performed as a result of changing the upper approach to include an emergency gate. Additional lock chamber experiments were conducted to determine the performance of a new port design suggested from a value engineering study of the Type 15 Design Filling and Emptying System for non standard lock valve operations. Non standard valve operations may be necessary for maintenance or a malfunctioning valve. All tests were performed with a 21.5-ft lift. The upper pool el was 601.6 and the lower pool el was 580.1.

15. SUBJECT TERMS

Hawser forces	Lock filling and emptying system	Soo locks
Lock coefficient	Lock intake	St. Mary's River
	Lock model	Vortex formation

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